ADA

ENGINE COLD START

INTERIM REPORT
TFLRF No. 469

by
Douglas M. Yost
Gregory A. T. Hansen

U.S. Army TARDEC Fuels and Lubricants Research Facility
Southwest Research Institute® (SwRI®)
San Antonio, TX

for
Eric Sattler
U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

Contract No. W56HZV-09-C-0100 (WD24 Task 3)

UNCLASSIFIED: Distribution Statement A. Approved for public release

September 2015

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Gary B. Bessee, Director
U.S. Army TARDEC Fuels and Lubricants
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EXECUTIVE SUMMARY

A fuel's cetane number is very important for the operation of modern diesel engines. The U.S. military currently uses petroleum-based jet fuels in diesel engine-powered ground vehicles and is studying the use of alternative jet fuels obtained from a variety of sources. Currently there is no cetane number specification for petroleum derived jet fuels as this property holds no significance for turbine engine operation. There does exist a minimum Derived Cetane Number of 40 for blended products, but it remains of interest to identify a window, or range, of cetane number which would be acceptable to ensure the reliable operation of diesel engine-powered military ground vehicles.

The TARDEC Fuels and Lubricants Research Facility (TFLRF) located at Southwest Research Institute identified 8 candidate fuels with cetane numbers ranging from 30 to 51. The fuels selected were JP-8 and synthetic blends.

These fuels were used for testing a GEP 6.5L turbocharged V-8 diesel engine operation in a cold box. This engine architecture is traditionally sensitive to cold start and was able to show large changes in operability between the fuels. At a relatively warm 40 °F, fuels below 44 CN were unable to start in the engine without the aid of glow plugs. At 20 °F and lower, none of the fuels were able to start the engine without the aid of glow plugs. At the -20 °F condition, the lowest cetane fuel caused cylinders 4 and 6 to cease firing, for 17 and 20 minutes respectively, until sufficient heat had built up in the engine to re-start combustion. This cylinder non-fire condition was more and more prevalent with colder temperatures and lower cetane number fuels.

The results from this work should help the military integrate emerging and future fuels into the supply chain.

FOREWORD/ACKNOWLEDGMENTS

The U.S. Army TARDEC Fuel and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, performed this work during the period July 2013 through September 2015 under Contract No. W56HZV-09-C-0100. The U.S. Army Tank Automotive RD&E Center, Force Projection Technologies, Warren, Michigan administered the project. Mr. Eric Sattler (RDTA-SIE-ES-FPT) served as the TARDEC contracting officer's technical representative and the project technical monitor.

The authors would like to acknowledge the contribution of the TFLRF technical and administrative support staff.

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ACRONYMS & ABBREVIATIONS

˚F	Degrees Fahrenheit
2-EHN	2-Ethylhexyl Nitrate
50MFB	50-Percent Mass Fraction Burned
ATDC	After Top Dead Center
ATJ	Alcohol to Jet
BM	Bulk Modulus
BMEP	Brake Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
CA50	Crank Angle 50 Timing (or the crank angle at which the 50% MFB occurs)
CAD	Crank Angle Degrees
CI	Cetane Index
CN	Cetane Number
CO	Carbon Monoxide
DAP	Data Acquisition
DCN	Derived Cetane Number
ESC	European Stationary Cycle
FTDSA	Fischer Tropsch Diesel from South Africa
FTDSH	Fischer Tropsch Diesel from Shell
GEP	General Engine Products
HC	Hydrocarbon
H/C	Hydrogen Atom to Carbon Atom Ratio
HCCI	Homogeneous Charge Compression Ignition
HRR	Heat Release Rate
IVC	Intake Valve Close
J/CAD	Joules per Crank Angle Degree
KVis	Kinematic Viscosity
LPP	Location of Peak Pressure
MFB	Mass Fraction Burned
MHRR	Maximum Heat Release Rate
NO_X	Oxides of Nitrogen (consisting of NO and NO_2)
OEM	Original Equipment Manufacturer
PQIS	Petroleum Quality Information System
RPM	Revolutions Per Minute
SOI	Start of Injection
SOW	Statement of Work
TDC	Top Dead Center
TFLRF	TARDEC Fuels and Lubricants Research Facility

1.0 INTRODUCTION

The goal of this program was to observe cetane-related performance trends and specifically, measure power, combustion characteristics, exhaust gas opacity, and the ability to start in cold environments.

2.0 EQUIPMENT

For the cold start study, a GEP 6.5L, V-8, turbocharged diesel engine, with a mechanical rotary pump-line-nozzle fuel injection system, and utilizing an indirect-injection combustion system was used. Indirect injection diesel engines have a high surface to volume ratio for the combustion chamber, and high gas velocities during compression that results in high heat transfer rates during the fuel injection event. To offset the high heat transfer rates, glow plugs and an elevated engine compression ratio are utilized to add heat into the pre-chambers during the injection event to augment ignition. Except for a thermostatically controlled cold start advance, the mechanical fuel injection system does not have any sensor feedback to alter injection timing to stabilize combustion. Fuel ignition quality was expected to impact engine starting and the time to a consistent idle speed with this engine.

2.1 MAINTENANCE

Prior to testing, the engine was filled with new coolant and oil. It was fully warmed up on JP-8 fuel prior to the first cold start test, to ensure any moisture in the crankcase was eliminated. Total test time on the engine was less than 50 hours, so no maintenance items were performed during the testing period.

3.0 TEST CYCLES

3.1 COLD START METHOD

The GEP 6.5L engine was operated on each fuel at 4 different temperatures: 40, 20, 0, and -20 °F. At each temperature, an attempt was made to start the engine without glow plugs. If that attempt was unsuccessful, the glow plugs were enabled for 10 seconds prior to cranking. The initial glow period was followed by a 40% duty cycle controlled glow plug output, during cranking and running, that operated until 10 minutes of elapsed run time had been achieved. This enabled a more direct comparison of the engine’s firing response to cetane number and ambient temperature.

The GEP engine was connected to an electric drive motor with an overrunning clutch so constant starting speeds could be simulated without relying on the OEM starter or battery. Once the engine was firing and spinning above a threshold rpm, the drive motor would stop and allow the engine to continue un-aided.

4.0 INSTRUMENTATION

Full engine instrumentation was employed including in-cylinder pressure. All relevant engine operating temperatures and pressures were recorded.

The high speed instrumentation for the GEP 6.5L engine consisted of the following:

- Kistler Cylinder Pressure Transducer, 6052B (Main-Chamber)
- Kistler 5018 Charge Amplifiers
- Kistler Fuel Line Pressure Transducer, 4065A1000 with matching pre-calibrated amplifier
- BEI Shaft Encoder (0.2 CAD)
- Wolff Instrumented Injector

The high speed data was recorded and post-processed by a SwRI High Speed DAQ. A SwRI PRISM DAQ system was used for engine control and data recording of the slow speed instrumentation. The exhaust opacity measurements were made by a Wager Company 6500iL inline opacity meter. The device fits in line with the exhaust and consists of a light source and a detector. The output (0-100%) is sent to the PRISM data acquisition system.

5.0 TEST FUELS

All of the fuels used in cold box testing are listed in Table 1 below. Two of the fuels were run in a previous companion program for the Air-Force. The remainder of the fuels were made, and fully reported on, in a separate task. For the purposes of this report, only the cetane numbers are reported.

It may be noted that both JP-8 fuels were supplied by a local refiner, and the difference in fuels was likely due to the large separation of time in which they were purchased. Two of the fuels, the 35% and 50% ATJ blends for the Army, were below the 40 cetane as required in the SOW. These were tested both as-is, and with a cetane additive to bring them up to 40.

Table 1. Selected Fuel Properties

Fuel	CI (D4737-10)	CI (D976-06 (2011))	DCN (D6890)	CN (D613)
JP-8 (For Air-Force Blending)		49.8		51.2
JP-8 (For Army Blending)	51.2	49.2	47.68	46.9
50% ATJ (w/ Air-Force JP-8)		51.6	38.75	33.0
50% ATJ (w/ Army JP-8)	55.0	51.0	37.04	31.3
50% ATJ + 2-EHN @ 0.5%				39.5
35% ATJ	53.8	50.3	41.02	36.4
35% ATJ + 2-EHN @ 0.08%				42.0
15% ATJ	52.5	49.9	45.15	44.2

6.0 CORRELATED RESULTS

In this section, results of the cold start are correlated in terms of time and exhaust opacity. They are listed in Figure 1 by decreasing temperature. As the engine warmed up and all cylinders started firing, the exhaust opacity, which indicates the presence of unburned hydrocarbons, generally decreased with time. The charts pick out the time values on each engine test for the exhaust opacity to decrease past a certain threshold. 90% opacity generally corresponds with 2 or more cylinders not firing. 50% opacity generally corresponds with 1 or 2 cylinders not firing. 10% opacity corresponds well with all cylinders firing.

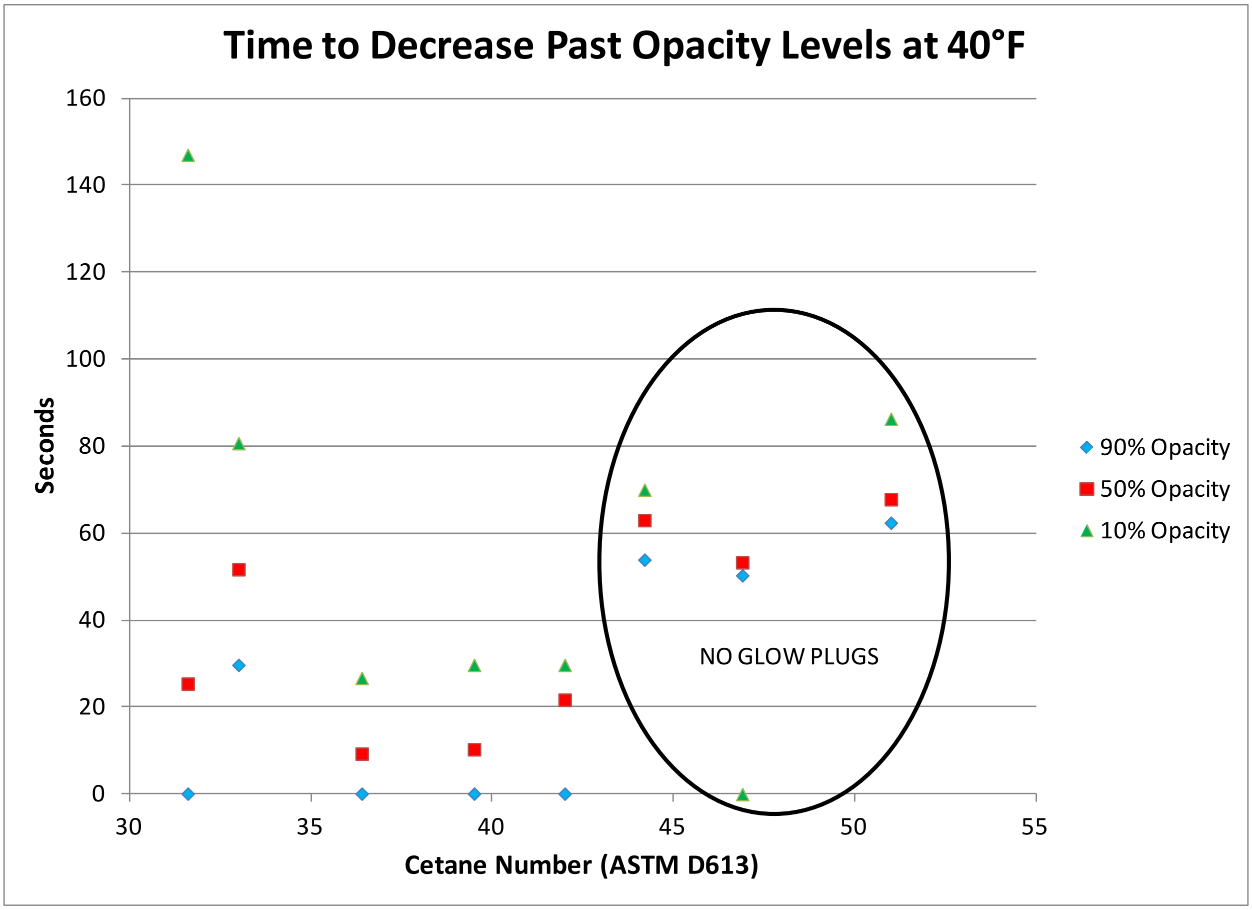

Figure 1: Correlated Results at 40 °F

The fuels with the three highest cetane numbers did not require the aid of glow plugs to start. These three tests were the only ones throughout the whole cold box program that did not require glow plugs. In a real-world application, the glow plugs will always be engaged to some extent prior to first firing, so the measured exhaust opacity values are likely artificially high for these three tests as a consequence of the laboratory test conditions.

At 40 °F, the cold start tests performed reasonably well for fuels with cetane numbers down to about 35, with only a few short instances of cylinder misfire. Below this cetane threshold, the time for the engine to become fully stable increased.

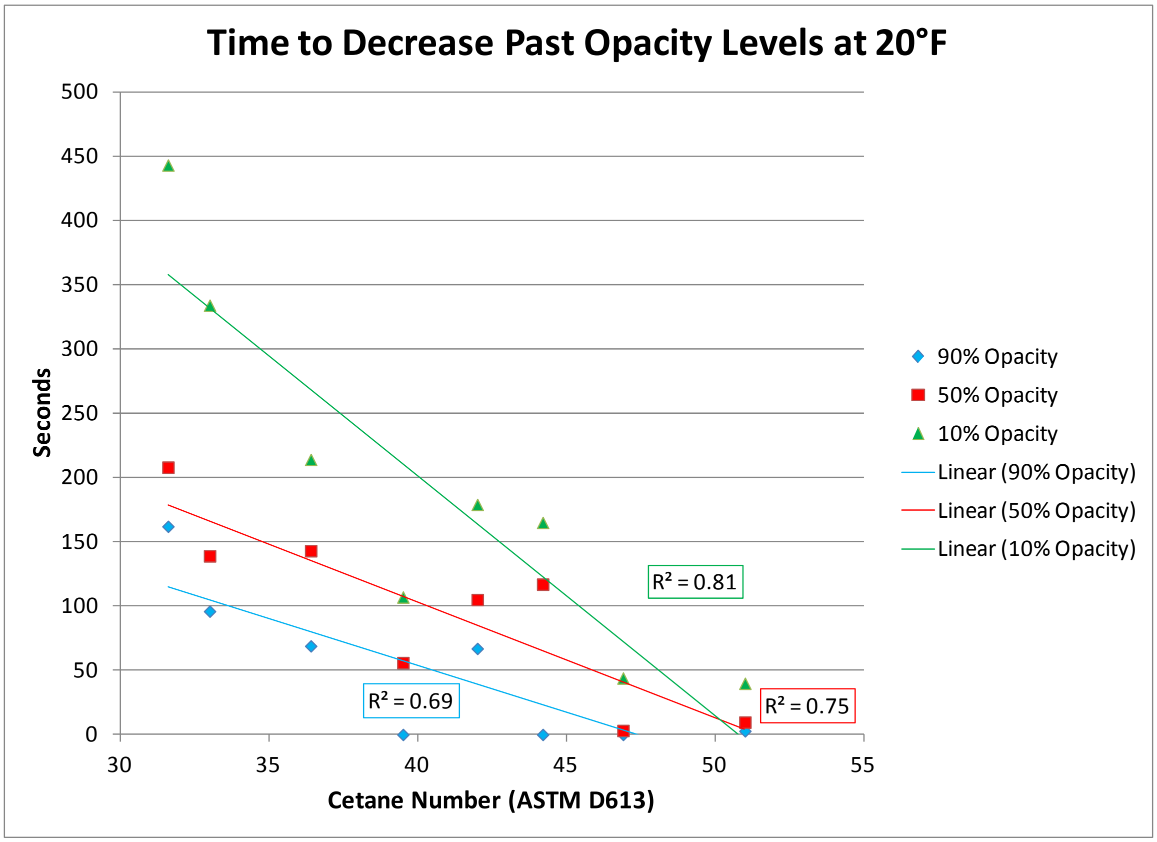

Figure 2: Correlated Results at 20 °F

Starting with the 20 °F testing conditions, as shown in Figure 2, a linear correlation emerges that relates cetane number and the time required for engine stability. The much steeper slope on the 10% opacity data set indicates that while most of the cylinders fire within a few minutes at low cetane, the last cylinder to fire takes an increasingly longer time (approaching 7.5 minutes).

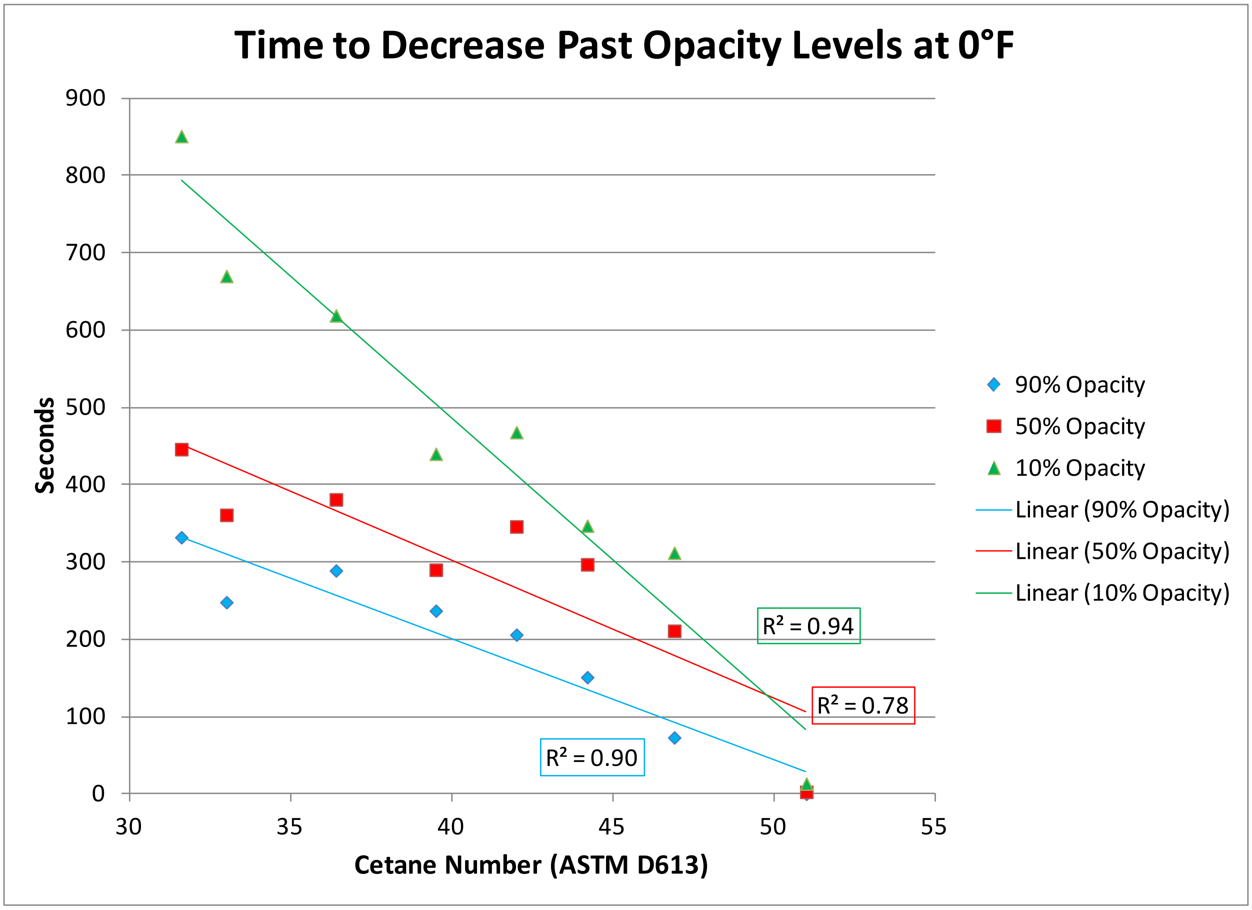

Figure 3: Correlated Results at 0 °F

In Figure 3, the graph for 0 °F is similar in form to the 20 °F graph, except for the large increase in the time scale. For the lowest cetane fuel, the engine took more than 14 minutes to reach full stability. In this data set, all of the linear curve fits have a much higher R-squared value.

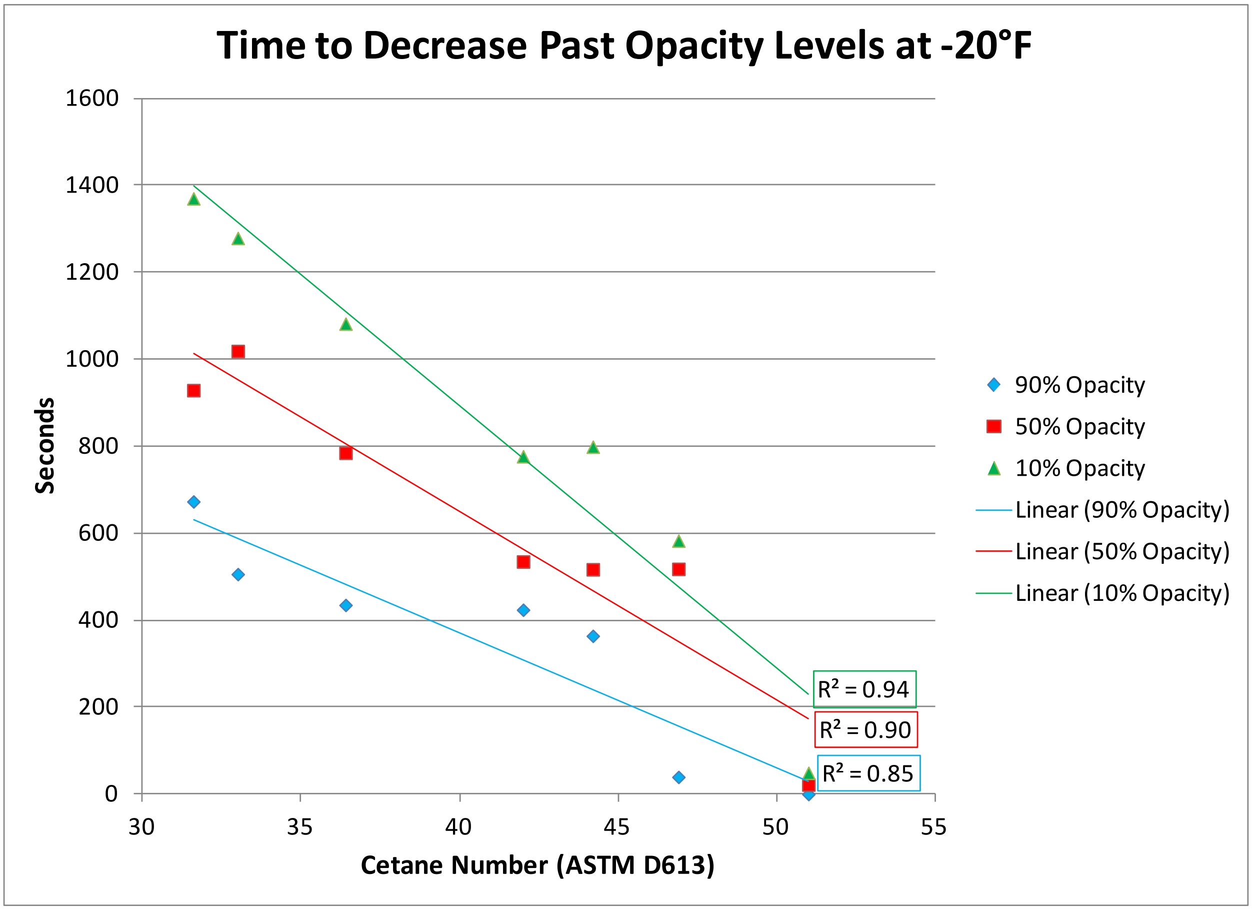

Figure 4: Correlated Results at -20 °F

At the -20 °F condition, seen in Figure 4, there is a strong correlation with cetane number and time to engine stability for all 3 data sets. The slopes are more closely aligned, indicating that there is now a larger issue with early engine stability. In practice, it was very difficult for the engine to start with fuels below 45 cetane. Under most conditions, the engine would be operating on a reduced number of cylinders for the first few minutes. For the lowest cetane fuel at the lowest temperature, 10 minutes of total required cranking time were required before the first cylinder fired. At this condition, it also took more than 23 minutes of idle time for the engine to achieve full stability. In a real world situation, the operator would request a higher throttle position and more engine speed in order to warm the engine up quickly. But, for the purposes of this program, repeatable comparisons were more desirable.

Table 2. Count of 2-Minute Cranking Events Prior to the Engine Firing

2-Minute Cranking Events Before Firing				
	Cold Box Temperature			
Cetane #	40° F	20° F	0° F	-20° F
51	0	1	1	1
46.9	0	0	3	4
44.2	0	0	2	3
42	0	1	1	4
39.5	0	1	3	n/a
36.4	0	1	2	3
33	0	1	1	2
31.6	0	2	2	5

A record was also made of how many starting attempts occurred prior to the engine firing. The control program was written so that if a minimum engine speed had not been achieved after 2 minutes of cranking, the cranking motor would power down and allow the engine to rest for 2 minutes before trying again. In Table 2, there is a very strong correlation between the number of required cranking events and temperature. There is little to no correlation between cranking events and cetane number. This indicates that the thermal energy delivered to the combustion chamber during cranking (cranking work changing to heat via friction, and direct heating through the glow plug) is a much stronger driver of the engine's ability to first fire than the chemical properties of the fuel. Once fired however, the fuel's composition take the lead in determining engine stability, as seen in the previous three figures.

7.0 INDIVIDUAL RESULTS

Detailed results of each cold start test are found in this section, and will be listed in order of decreasing cetane number.

7.1 GEP COLD START ON 51.2 CETANE FUEL

At 40 °F, the engine was able to start without the aid of glow plugs. However, as seen in Figure 5, the engine was firing intermittently on 4 cylinders before fully starting. A few seconds after starting, the engine was able to achieve a steady rpm. Cylinders 7 and 8 were the last to fire continuously, and the opacity decreased rapidly to zero once combustion stabilized.

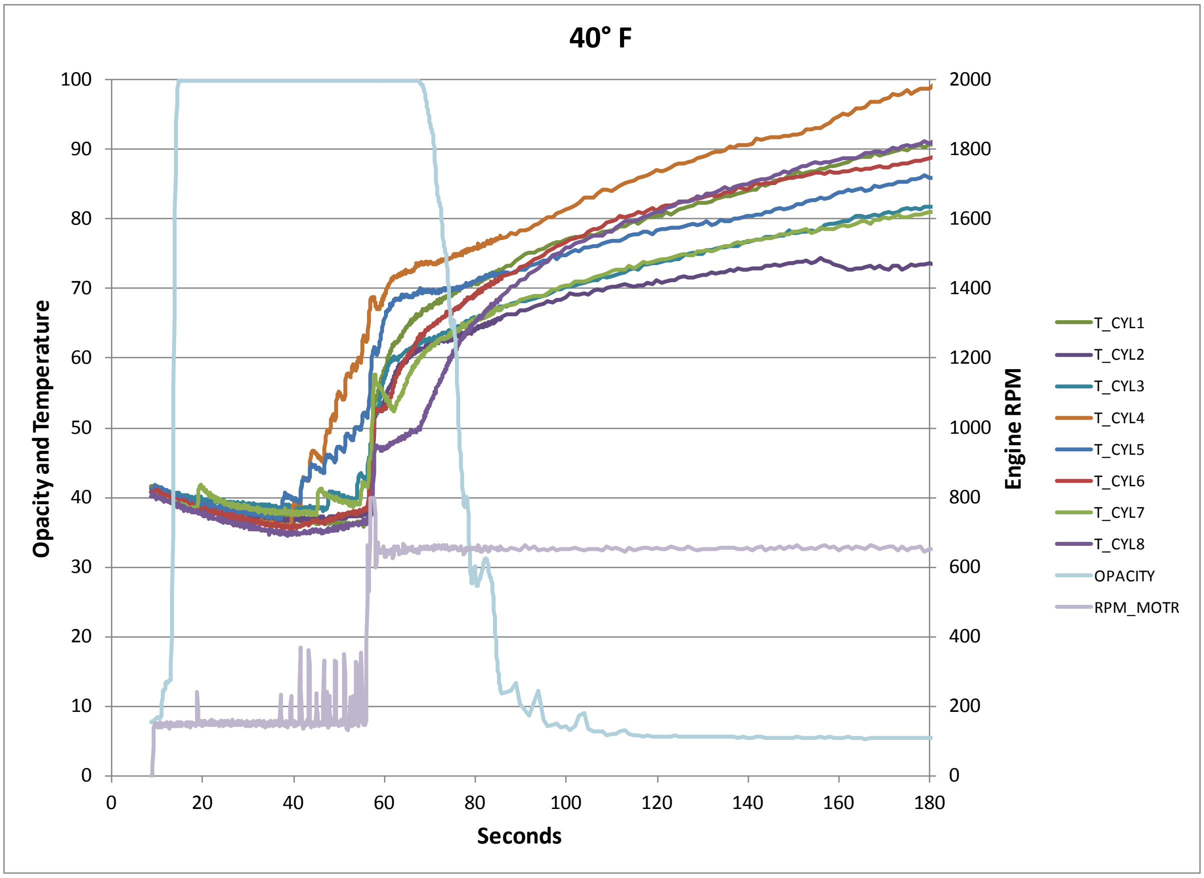

Figure 5. 51.2 Cetane Cold Start at 40 °F

At 20 °F, the engine was only able to start with the use of glow plugs. As seen in Figure 6, the engine started immediately with no hesitation, firing on all cylinders. The opacity took about a minute to drop below 10 percent as the individual cylinders continued to warm up.

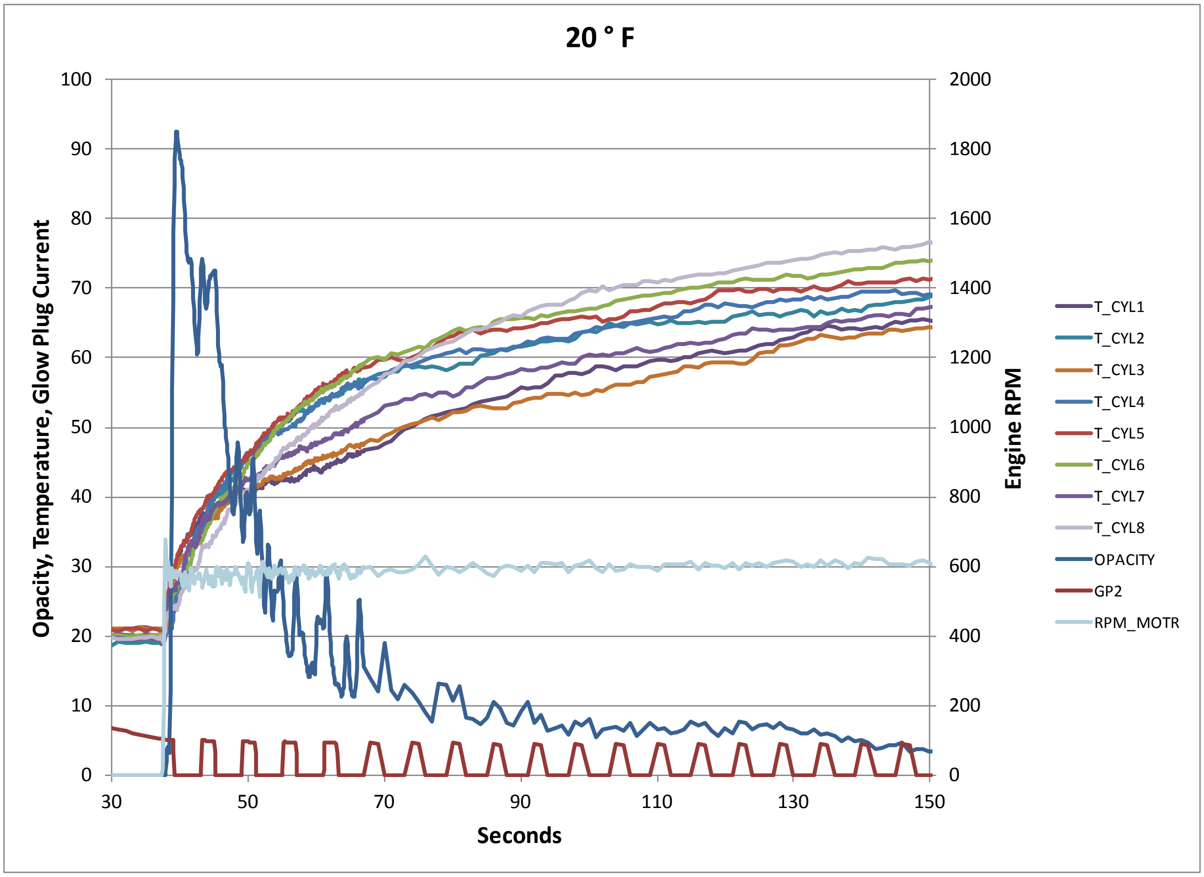

Figure 6. 51.2 Cetane Cold Start at 20 °F

At 0 °F, the engine was again only able to start with the use of glow plugs. As seen in Figure 7, the engine started immediately with no hesitation, firing on all cylinders. The opacity took about 10 seconds to drop below 10 percent as the individual cylinders continued to warm up. The rpm started a bit lower due to the increased engine friction of the viscous oil, but as the temperatures came up, so did the speed. It is surmised that the engine warms up faster at lower temperatures due to the increased viscosity of the fuel. The fuel's viscosity directly impacts the delivered volume. This is a result of the internal design of the rotary injection pump.

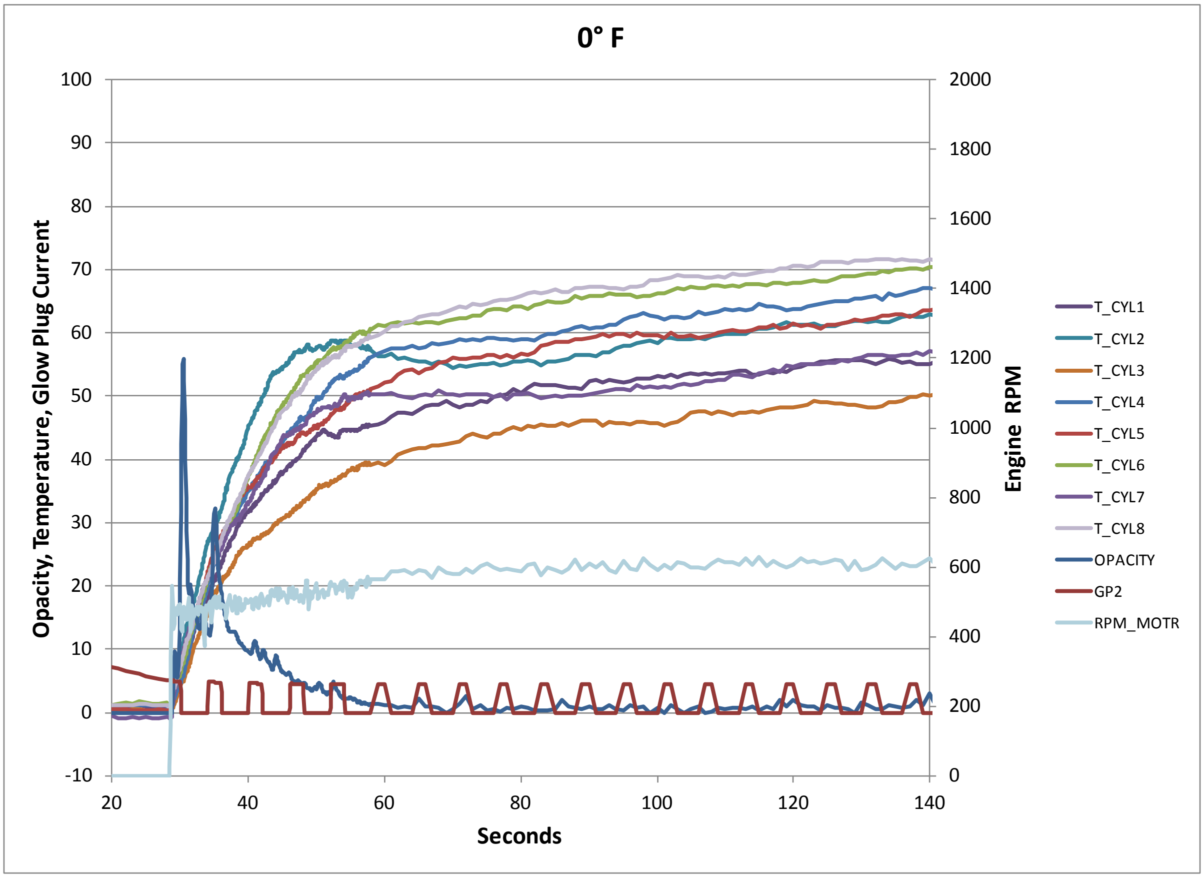

Figure 7. 51.2 Cetane Cold Start at 0 °F

At -20 °F, the engine was again only able to start with the use of glow plugs. As seen in Figure 8, the engine started immediately with no hesitation, firing on all cylinders. The opacity took about 1 minute to drop below 10 percent as the individual cylinders continued to warm up. The rpm started even lower than before due to the increased engine friction of the viscous oil, but as the temperatures came up, so did the speed. At this run condition, however cylinder 7 stopped firing after 2.5 minutes and did not re-ignite for another 2.5 minutes even with the glow plugs engaged on their duty cycle timer. After stable combustion on all 8 cylinders, the idle rpm was just over 600.

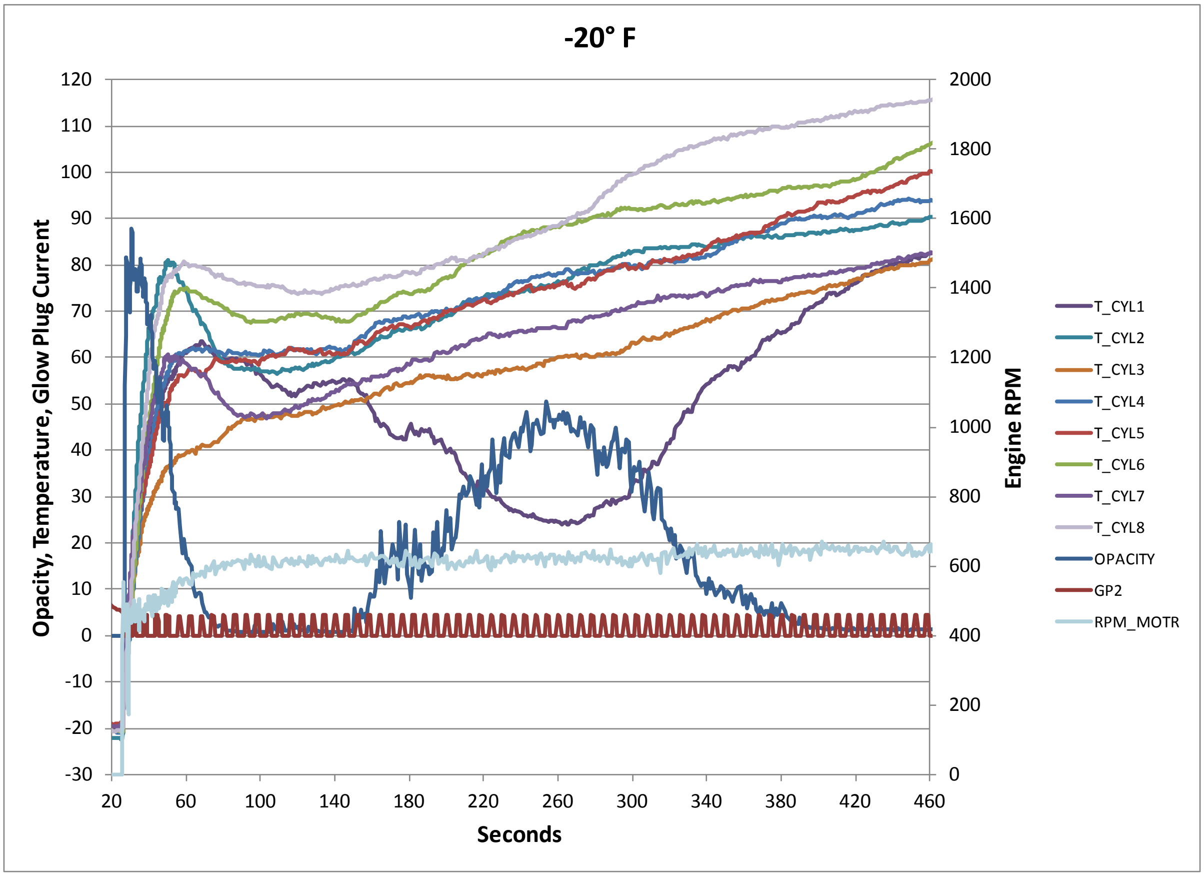

Figure 8. Cetane Cold Start at -20 °F

For this particular engine installation, it is not unexpected for a cylinder to stop firing at low temperatures. As mentioned previously, diesel engines with pre-chamber architecture are particularly sensitive to cold start regimes. Over all of the cold start tests performed, cylinders 1,2,4,6,7,and 8 all took turns discontinuing combustion after the initial start event. In addition, this particular engine installation is likely more sensitive to cold running operation due to the lack of accessory drive loads that are typically present in an actual vehicle.

7.2 GEP COLD START ON 46.9 CETANE FUEL

At 40 °F, the engine was able to start without the aid of glow plugs. However, as seen in Figure 9, the engine was firing intermittently on all 8 cylinders before fully starting. A few seconds after starting, the engine was able to achieve a steady rpm. Cylinders 7 and 8 were the last to fire continuously, and the opacity decreased rapidly to zero once combustion stabilized. There was an observed rise in opacity, but this was due to clouding of the camera window from residual soot in the piping, and was cleaned out prior to the next run.

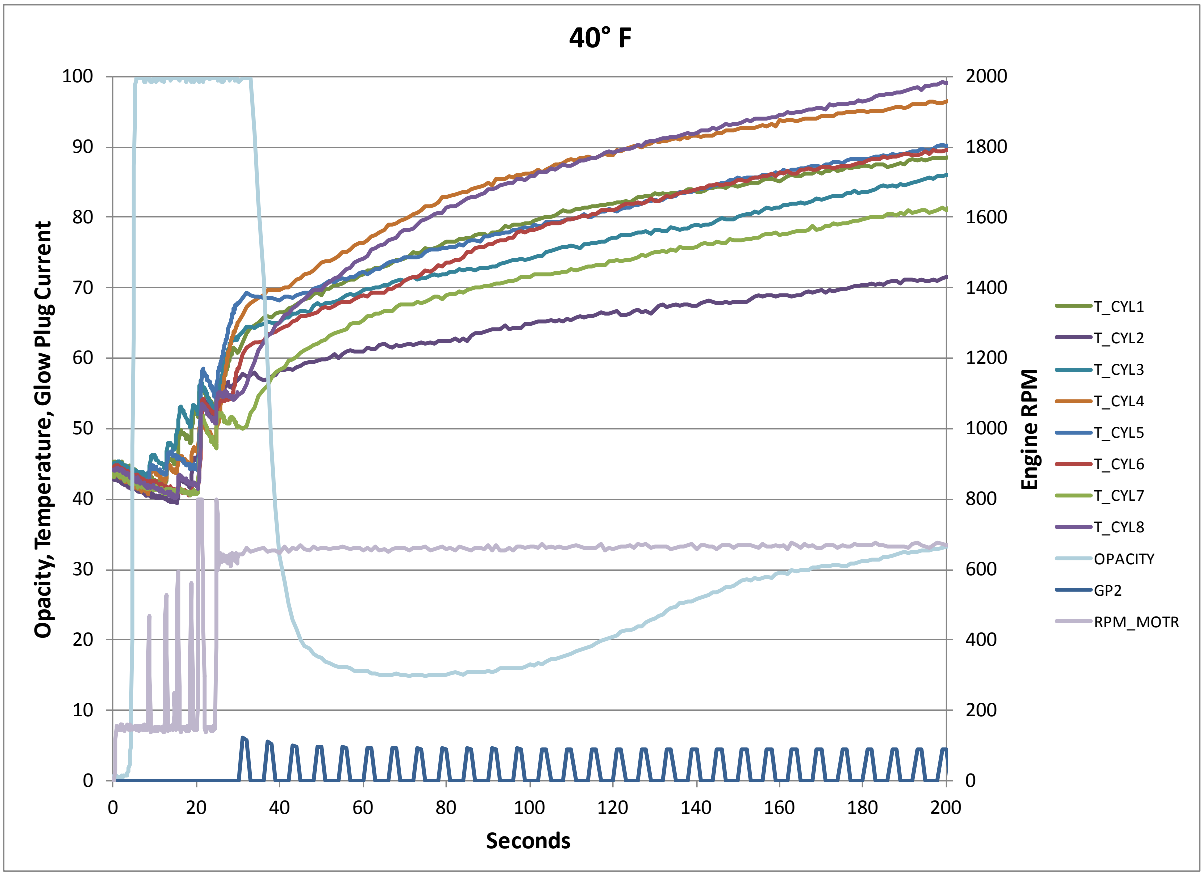

Figure 9. 46.9 Cetane Cold Start at 40 °F

At 20 °F, the engine was only able to start with the use of glow plugs. As seen in Figure 10, the engine started immediately with no hesitation, firing on all cylinders. Cylinder 1 fired intermittently for the first 30-40 seconds, and then fired continuously. The opacity took about 50 seconds to drop below 10 percent as the engine continued to warm up.

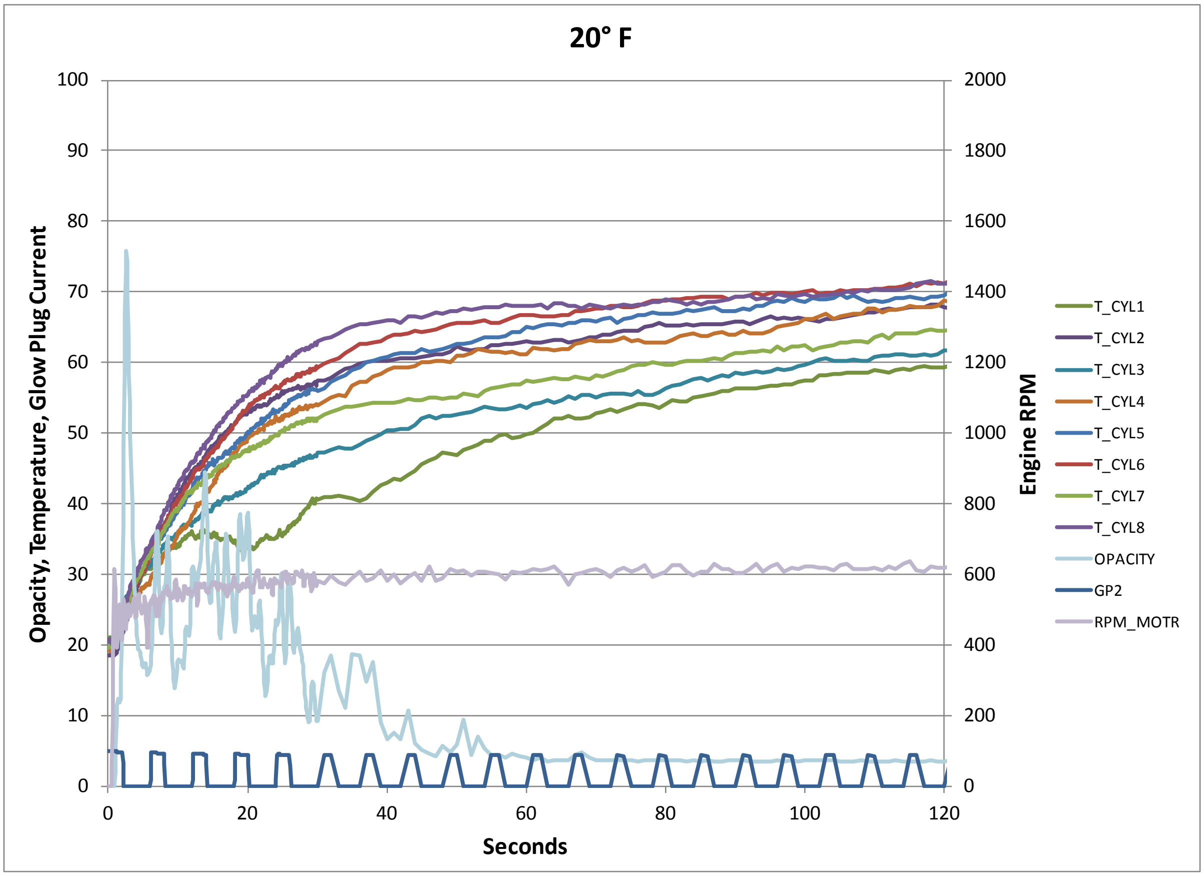

Figure 10. 46.9 Cetane Cold Start at 20 °F

At 0 °F, the engine was only able to start with the use of glow plugs. As seen in Figure 11, the engine had hesitation starting and firing on all cylinders. All of the cylinders fired from 10 to 15 seconds, with cylinder 7 dropping out first. At 30 seconds or runtime, all 8 cylinder started firing, but again cylinder 7 stopped after about 10 seconds. At the 70 second mark, cylinder 2 stopped firing for about 20 seconds, and cylinder 6 had a few non-fired cycles between 80 and 90 seconds as well. At the 90 second mark, cylinders 1 and 4 started to have some non-firing events as well that were driving the exhaust gas temperatures down. The data set continues in Figure 12.

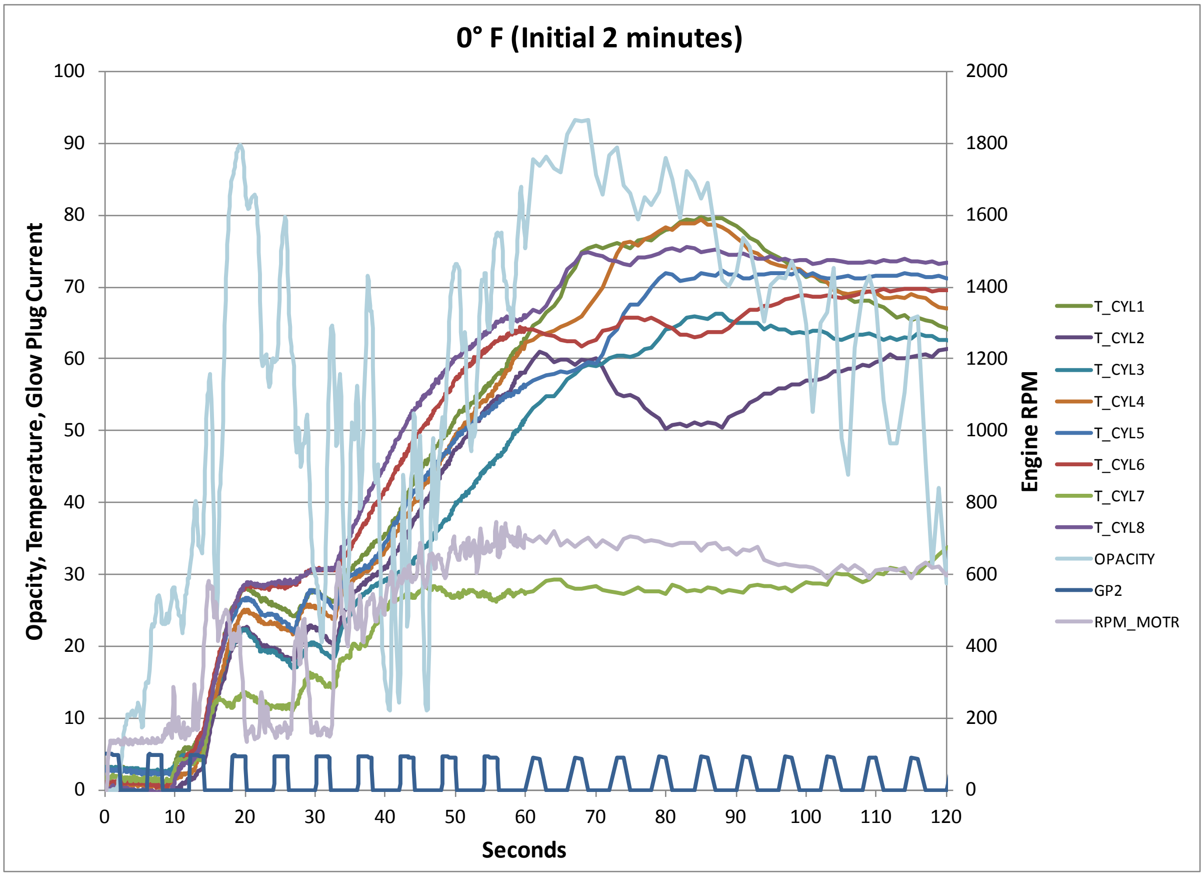

Figure 11. 46.9 Cetane Cold Start at 0 °F – Initial 2 minutes

By about the 120 second mark, it is clear that cylinder 7 had resumed firing, and cylinder 1 had ceased. There were some interspersed non-firing events among cylinders 4, 6, and 8, but they stayed running. Cylinder 1 however ceased firing completely until the 260 second mark when it started to re-light. This intermittent operation continued until full re-light around the 360 second mark.

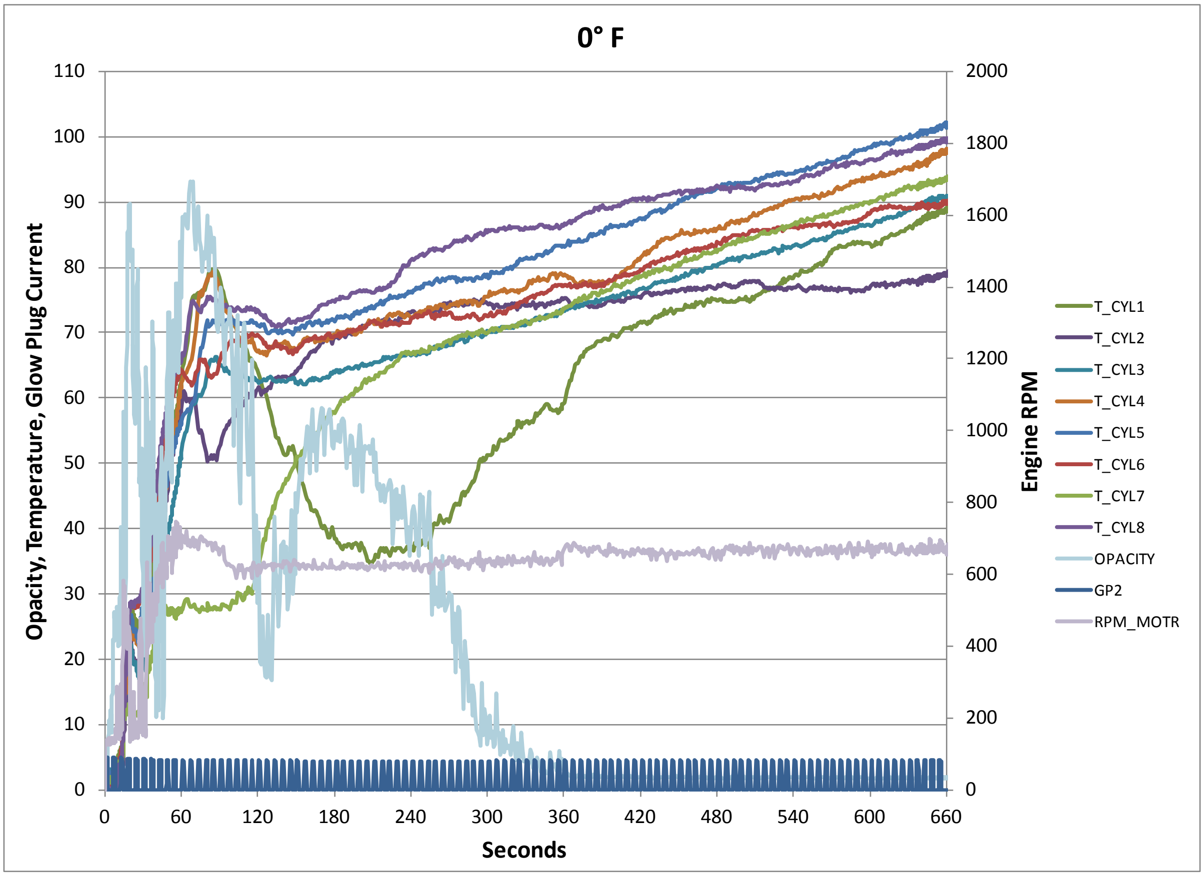

Figure 12. 46.9 Cetane Cold Start at 0 °F

At -20 °F, the engine was only able to start with the use of glow plugs. As seen in Figure 13, the engine had only a few firing events until starting and firing on all cylinders at about 35 seconds. All of the cylinders fired continuously until the 80 second mark when cylinder 1 cut out. The data set continues in Figure 14.

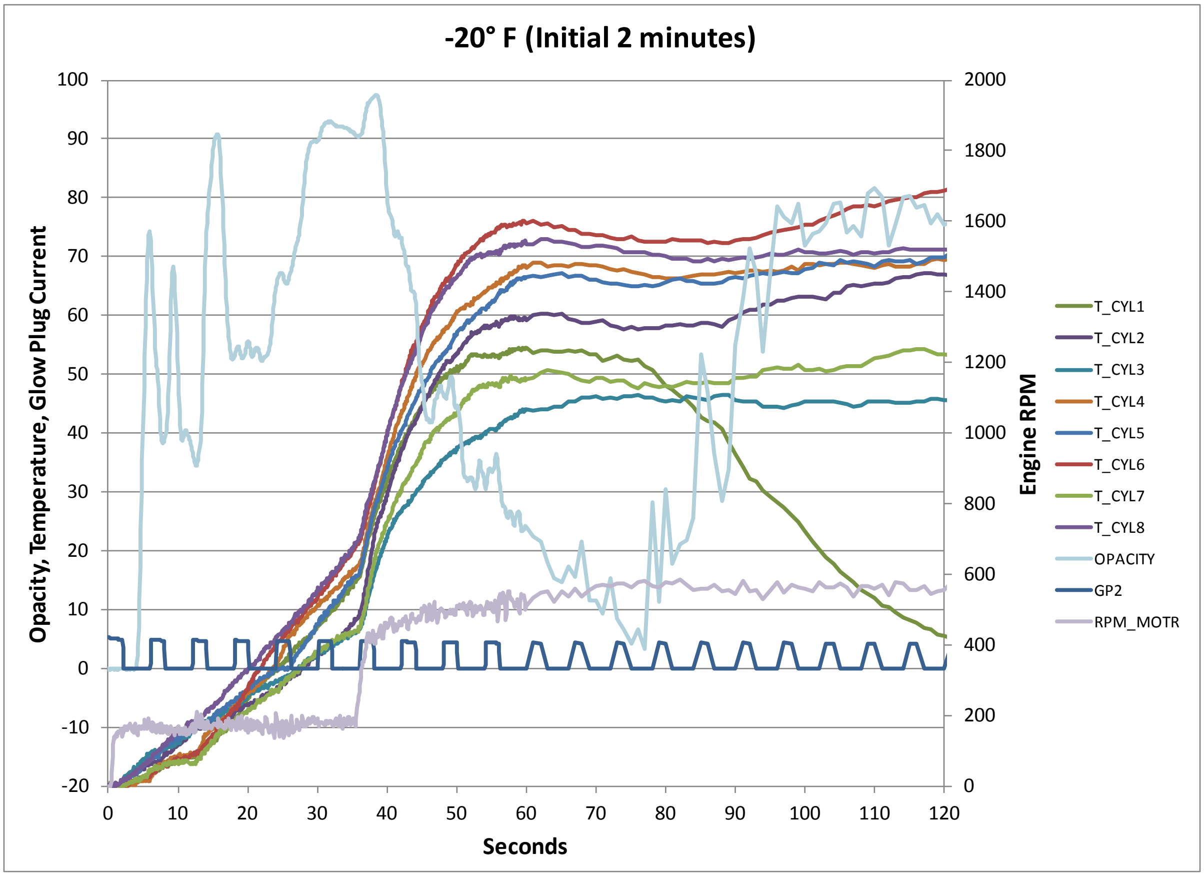

Figure 13. 46.9 Cetane Cold Start at -20 °F – Initial 2 minutes

Cylinder 3 also cut out, but only briefly from about 230 to 290 seconds. Cylinder 1 attempted to re-light starting at 435 seconds, and was running continuously after 780 seconds.

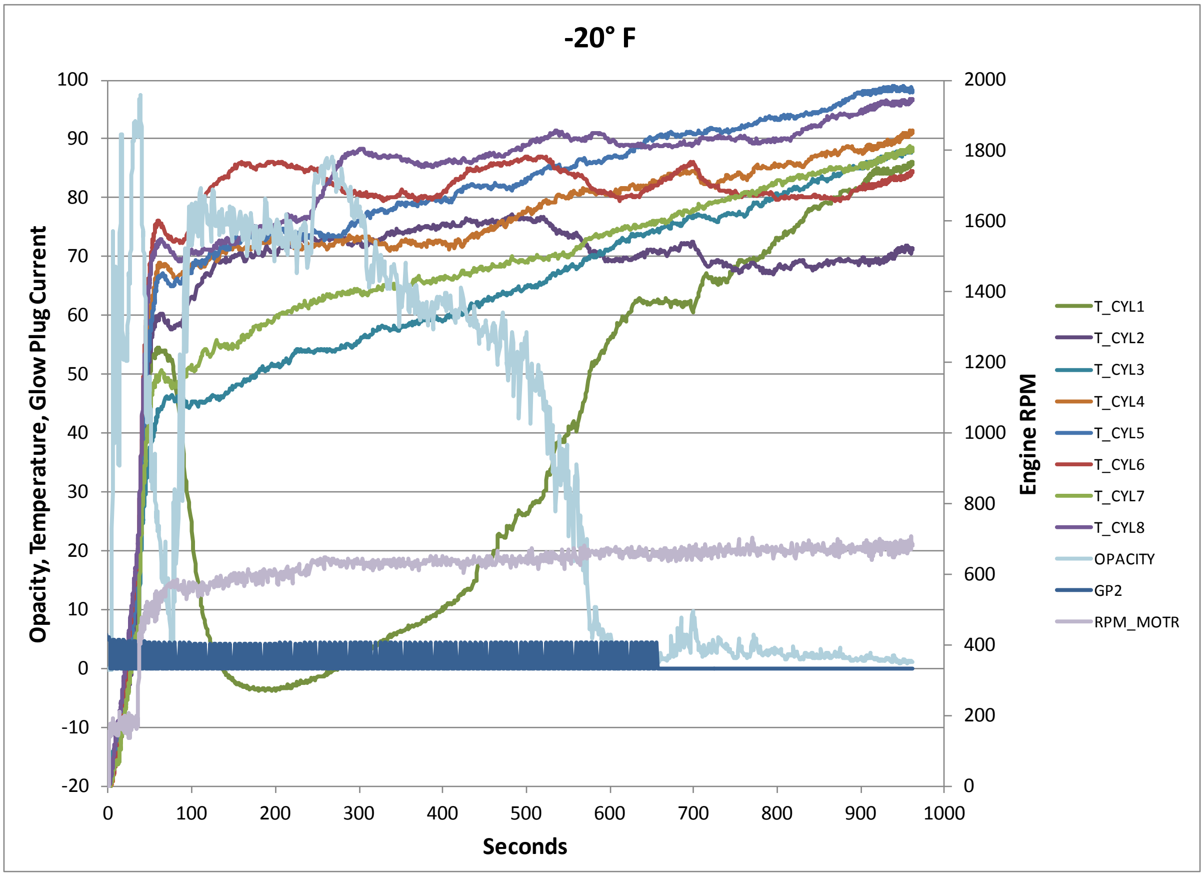

Figure 14. 46.9 Cetane Cold Start at -20 °F

7.3 GEP COLD START ON 44.2 CETANE FUEL

At 40 °F, the engine was able to start without the aid of glow plugs. However, as seen in Figure 15, the engine was firing intermittently on 2 cylinders before fully starting. A few seconds after starting, the engine was able to achieve a steady rpm. Cylinders 6 and 8 were the last to fire continuously, and the opacity decreased rapidly to zero once combustion stabilized.

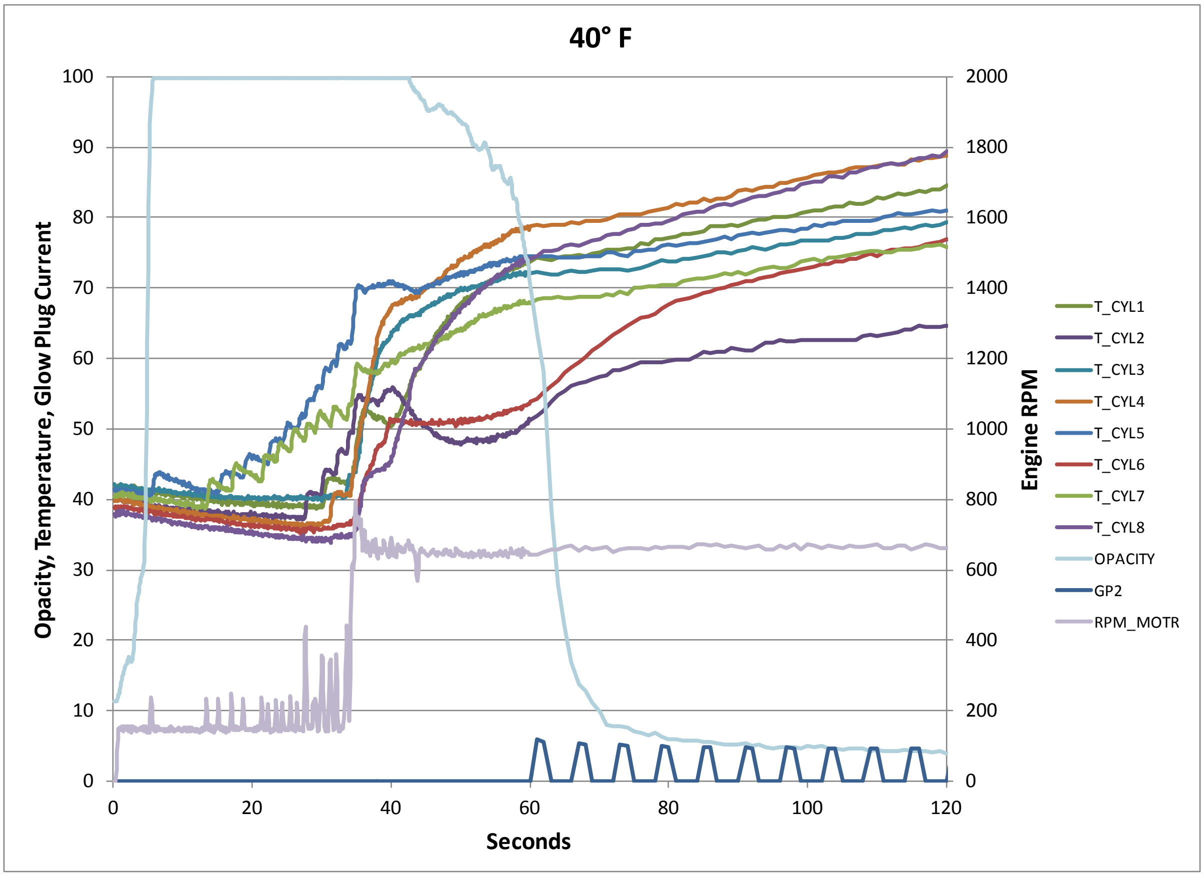

Figure 15. 44.2 Cetane Cold Start at 40 °F

At 20 °F, the engine was only able to start with the use of glow plugs. As seen in Figure 16, the engine started immediately with no hesitation, firing on all cylinders. Cylinders 1 and 6 fired intermittently for the first 30 seconds. Cylinder 6 then fired continuously while cylinder 1 cut out for about a minute. Cylinder 1 then fired intermittently until about 150 seconds of runtime had elapsed and then fired continuously. The opacity decreased rapidly to zero once combustion stabilized.

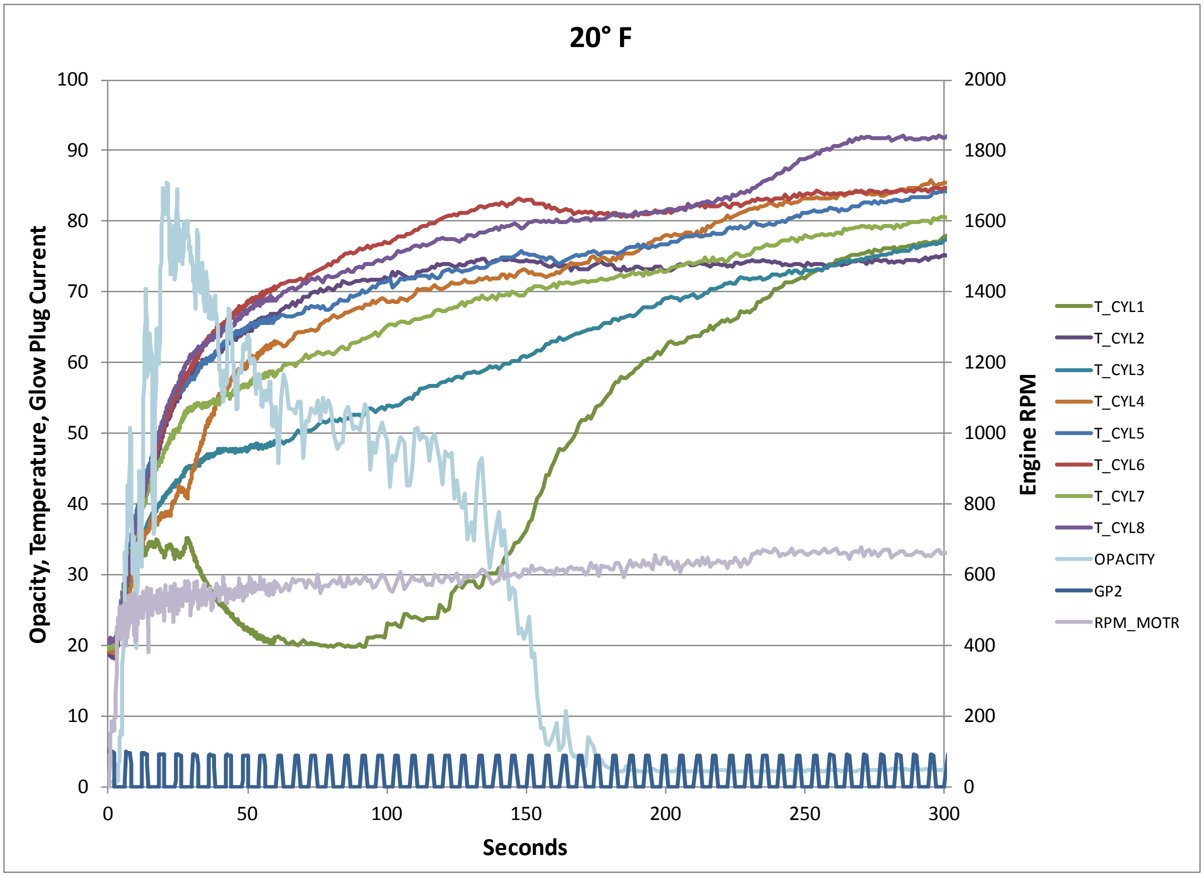

Figure 16. 44.2 Cetane Cold Start at 20 °F

At 0 °F, the engine was only able to start with the use of glow plugs. As seen in Figure 17, the engine started immediately with no hesitation, firing on all cylinders. Cylinder 4 cut out at about the 15 second mark. Cylinder 6 then attempted re-light from 200 to 300 seconds. The opacity decreased rapidly to zero once combustion stabilized at around 300 seconds.

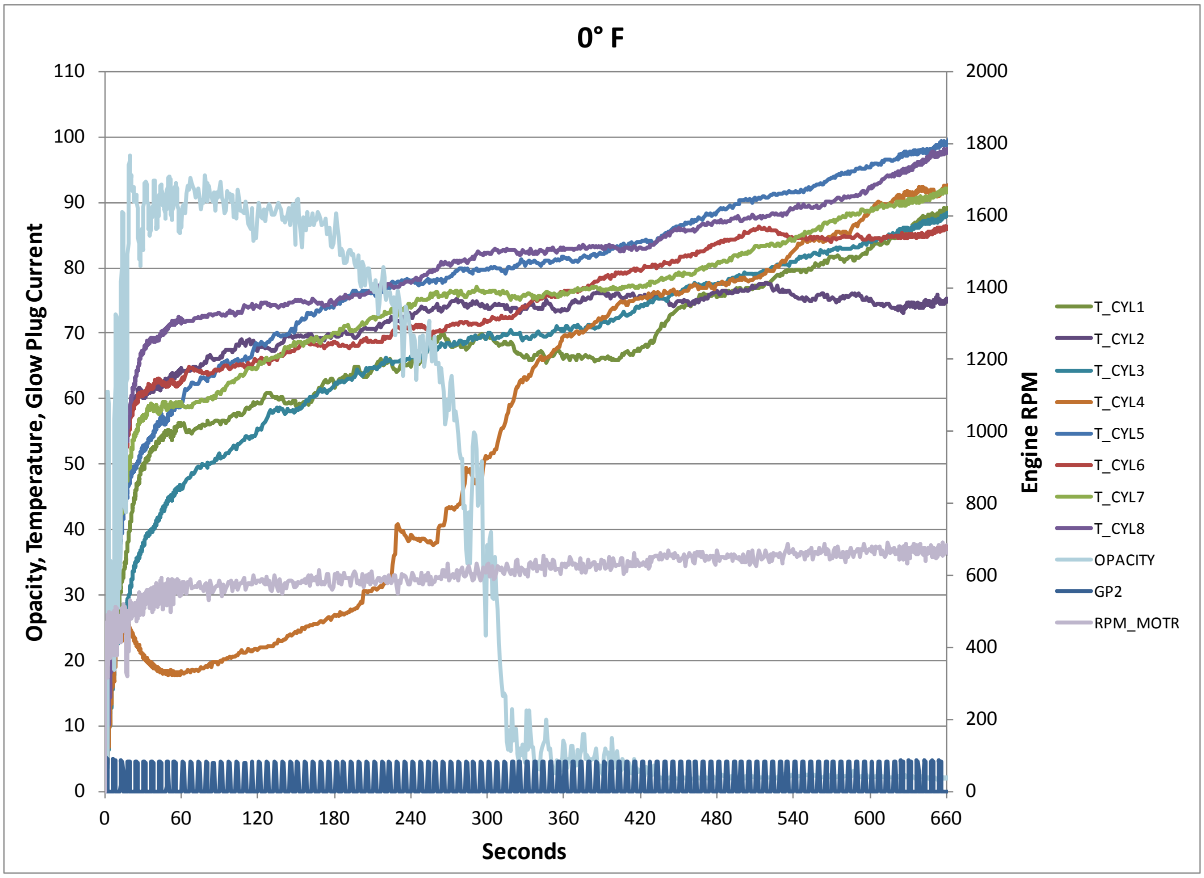

Figure 17. 44.2 Cetane Cold Start at 0 °F

At -20 °F, the engine was only able to start with the use of glow plugs. As seen in Figure 18, the engine had only a few firing events until starting and firing on all cylinders at about 30 seconds. 5 seconds later, cylinder 7 cut out, followed by cylinder 1 at the 60 second mark. The data set continues in Figure 19 on the following page.

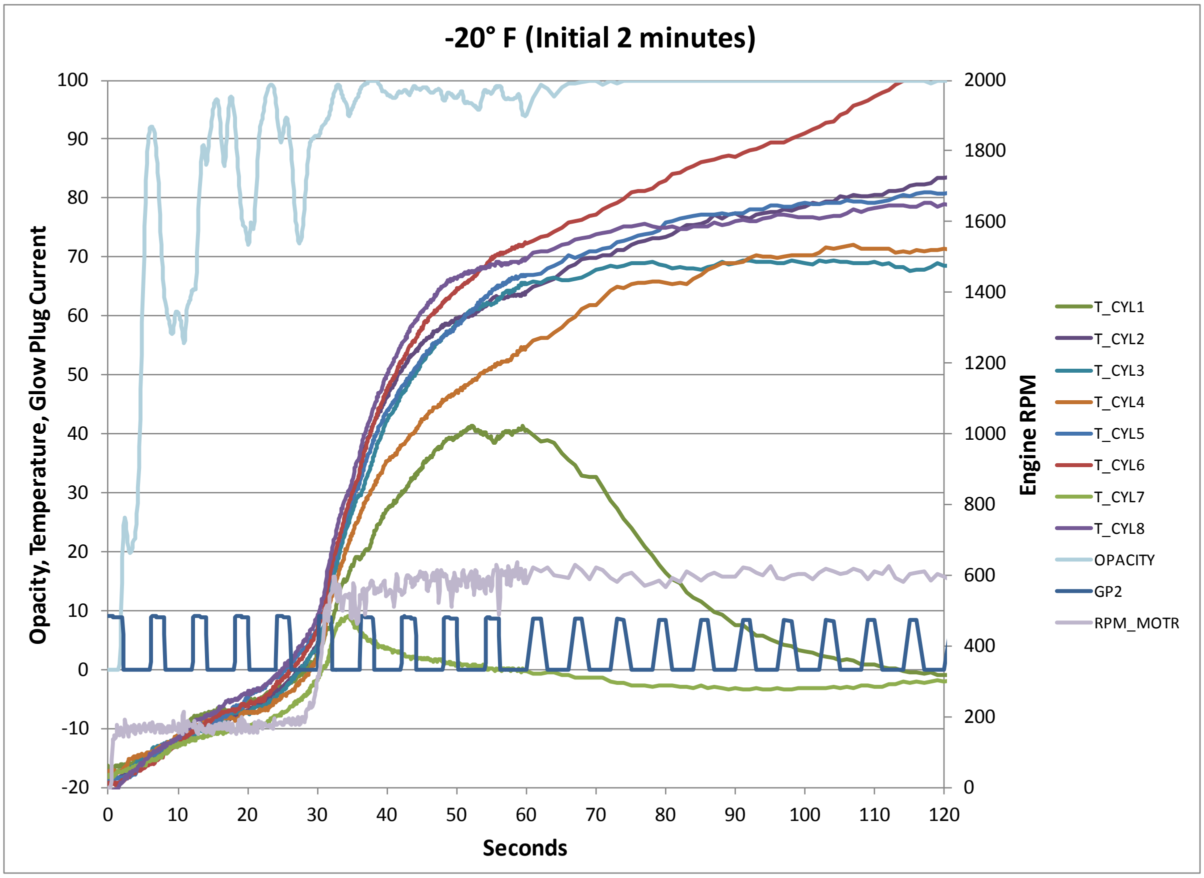

Figure 18. 44.2 Cetane Cold Start at -20 °F – Initial 2 minutes

Cylinder 7 started to re-light after 310 seconds of runtime, and was running continuously after 460 seconds. Cylinder 1 attempted re-light from 580 to 660 seconds. The successful re-light started at 690 seconds, and cylinder 1 was running continuously after 730 seconds.

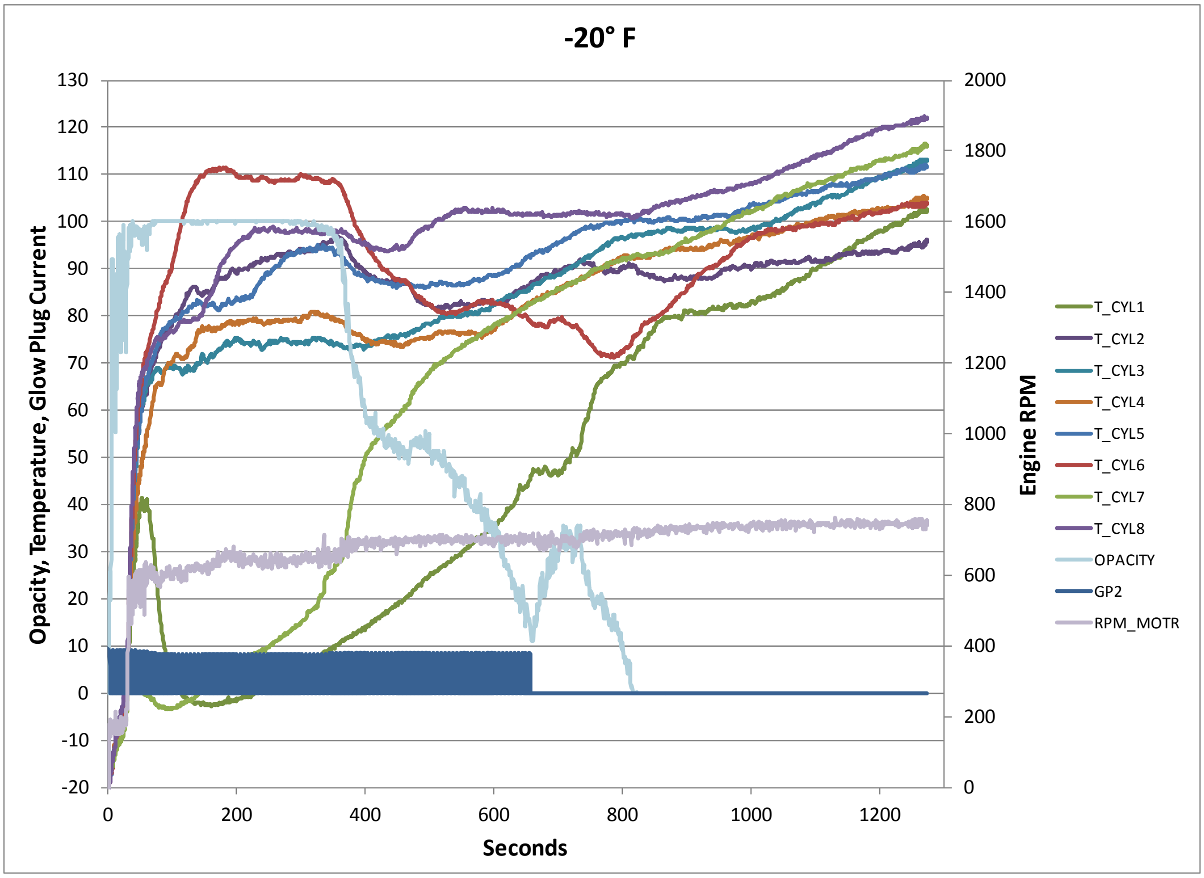

Figure 19. 44.2 Cetane Cold Start at -20 °F

7.4 GEP COLD START ON 42.0 CETANE FUEL

At 40 °F, and with all fuels from this point onward, the engine was only able to start with the aid of glow plugs, and in this case the engine fired immediately on all cylinders. However, a few seconds after starting, cylinders 1 and 8 stopped firing (Figure 20). Cylinder 8 fired continuously after about 20 seconds, and cylinder 1 fired continuously after about 30 seconds. Once the last cylinder fired continuously, the opacity decreased rapidly to zero.

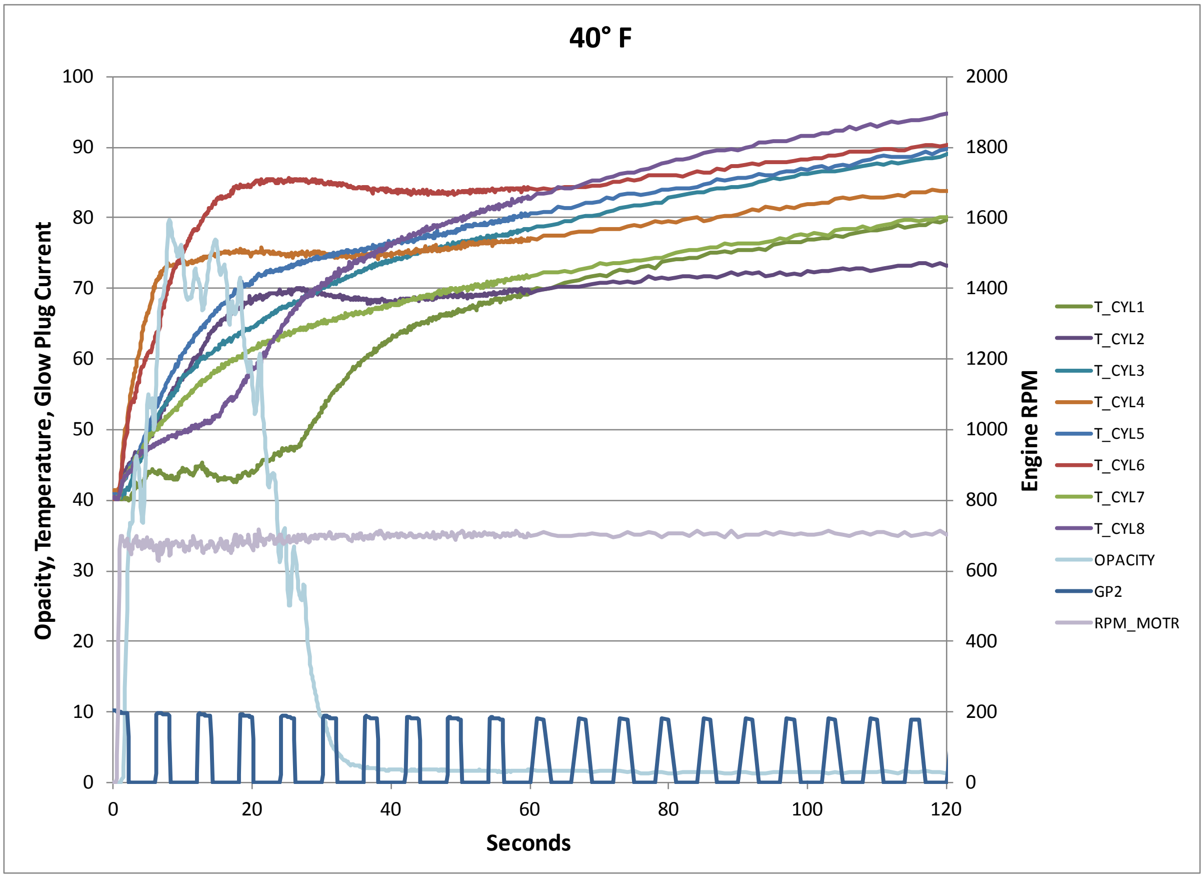

Figure 20. 42 Cetane Cold Start at 40 °F

At 20 °F, the engine was only able to start with the use of glow plugs. As seen in Figure 21, the engine started immediately with no hesitation, firing on all cylinders. Cylinders 1 and 8 both cut out at about the 10 seconds mark. Cylinder 8 then attempted relight from 30 to 80 seconds and fired continuously after. The data set continues in Figure 22on the following page.

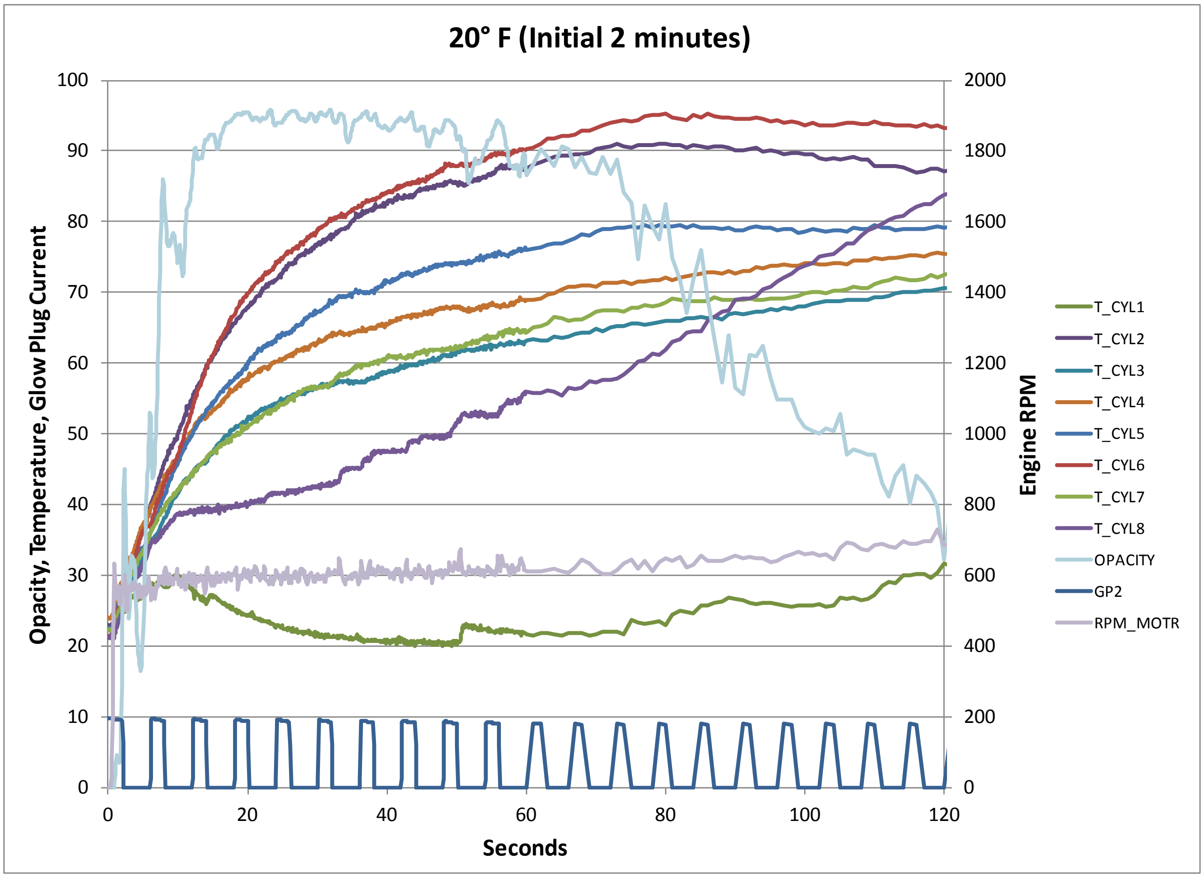

Figure 21. 42 Cetane Cold Start at 20 °F – Initial 2 minutes

Cylinder 1 attempted relight several times from 30 to 180 seconds. It then fired continuously after about 180 seconds of runtime. The opacity decreased rapidly to zero once combustion stabilized.

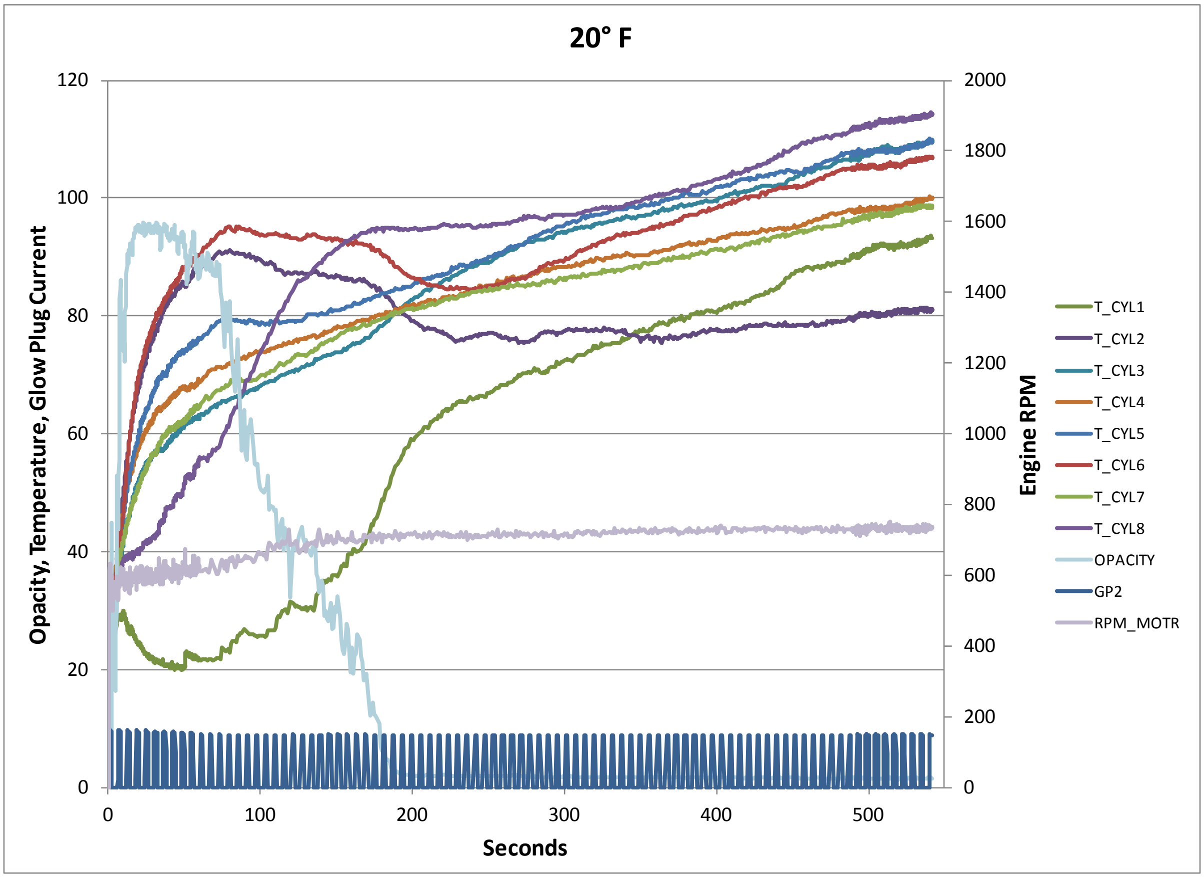

Figure 22. 42 Cetane Cold Start at 20 °F

At 0 °F, the engine was only able to start with the use of glow plugs. As seen in Figure 23, the engine started immediately with no hesitation, firing on all cylinders. Cylinders 1 and 3 cut out at about the 15 second mark, followed by cylinder 8 at the 25 second mark. Cylinder 3 quickly re-lit by the 30 second mark. The data set continues in Figure 24 on the following page.

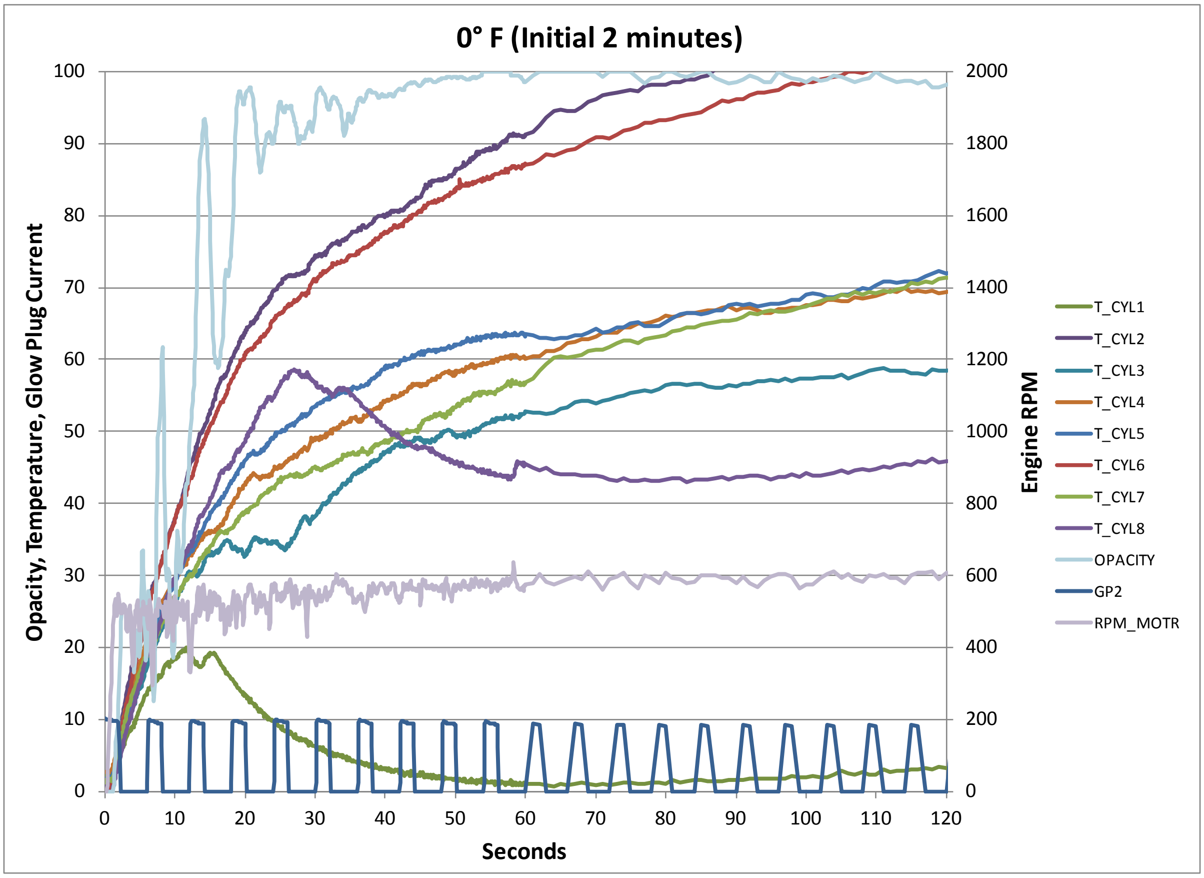

Figure 23. 42 Cetane Cold Start at 0 °F – Initial 2 minutes

Cylinder 8 attempted re-light from 180 to 320 seconds and was running continuously beyond 320 seconds. Cylinder 1 had one firing event at 180 seconds and was off for several minutes. From 330 to 425 seconds cylinder 1 attempted to re-light. Opacity quickly dropped after cylinder 1 was firing continuously from 425 seconds onward.

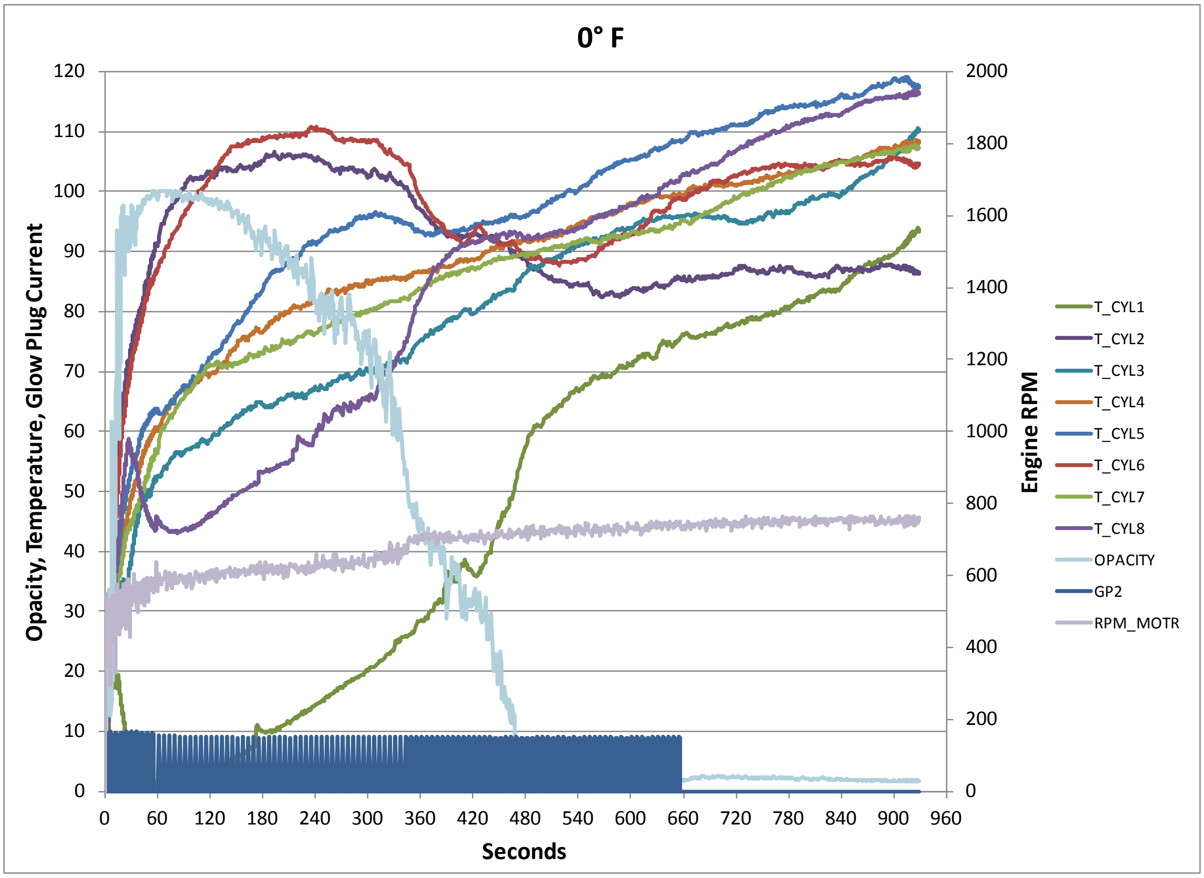

Figure 24. 42 Cetane Cold Start at 0 °F

At -20 °F, the engine was only able to start with the use of glow plugs. As seen in Figure 25, the engine started immediately with no hesitation, firing on all cylinders. Cylinders 2, 7, and 8 fired continuously, while cylinder 5 and 6 had a couple of misfires. Cylinders 1 and 3 cut out at the 10 second mark, followed by cylinder 4 at the 20 second mark. The data set continues in Figure 26 on the following page.

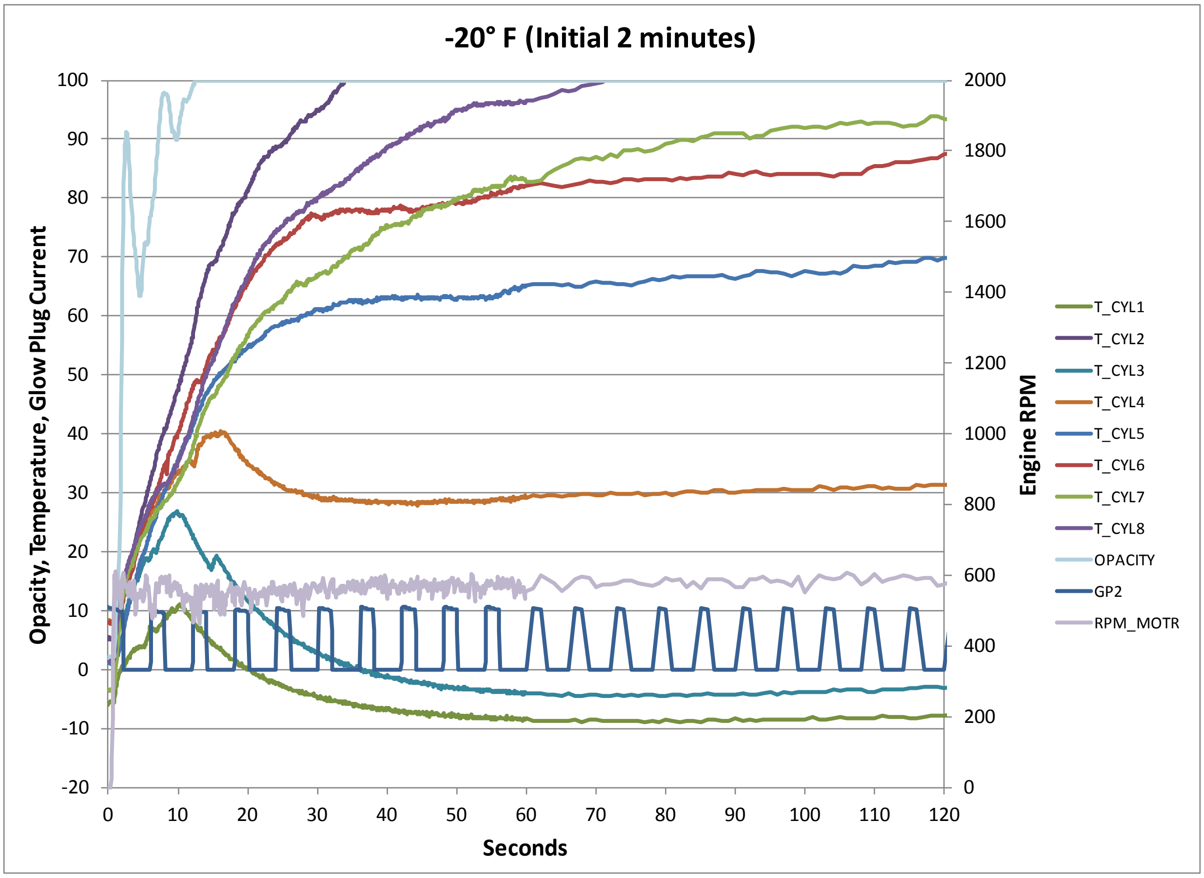

Figure 25. 42 Cetane Cold Start at -20 °F – Initial 2 minutes

Cylinder 4 was the first to attempt re-light starting at about the 220 second mark. It was running continuously after 350 seconds. Cylinder 3 started to re-light at the 350 second mark and was running continuously after 420 seconds. Cylinder 1 did not start to re-light until after 550 seconds of runtime. It was finally firing continuously after 630 seconds.

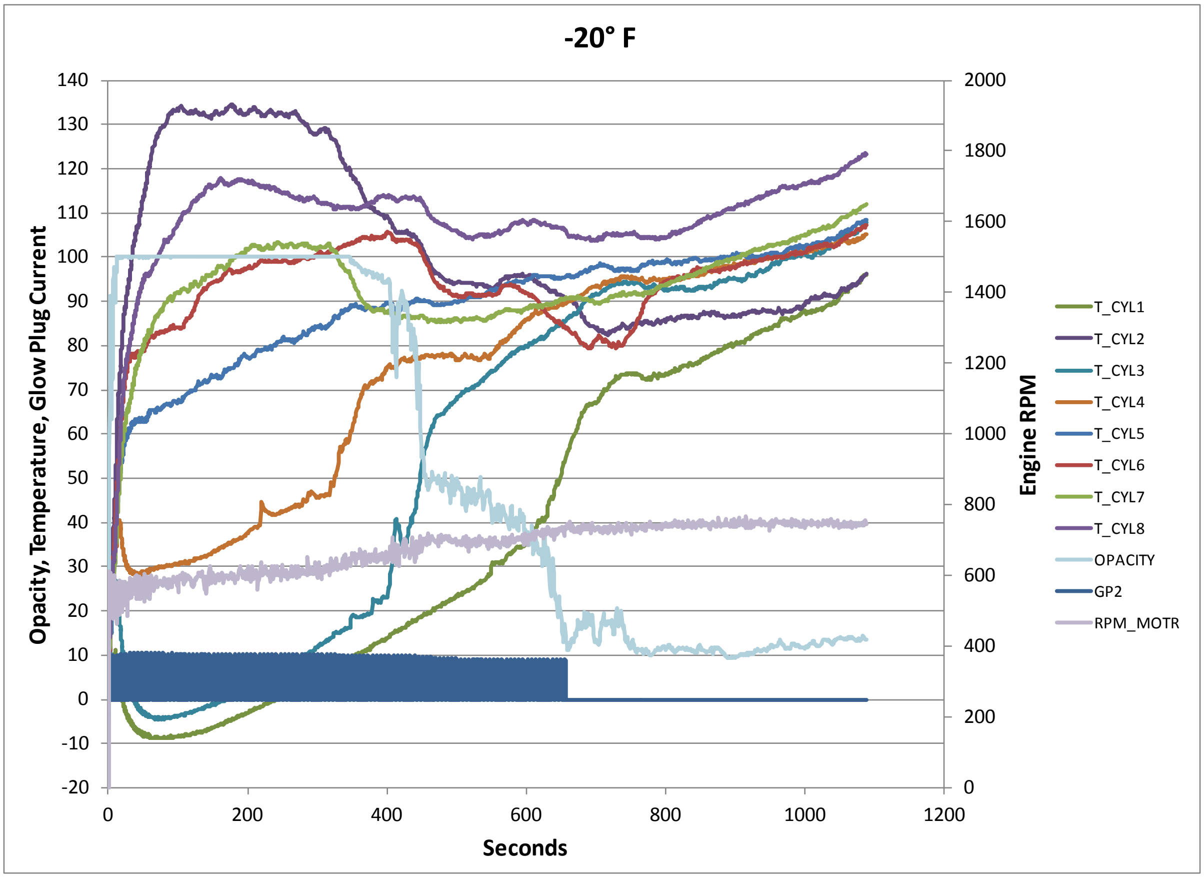

Figure 26. 42 Cetane Cold Start at -20 °F

7.5 GEP COLD START ON 39.5 CETANE FUEL

At 40 °F, and with the aid of the glow plugs, the engine fired immediately on all cylinders (Figure 27). However, a few seconds after starting, cylinders 6 and 8 stopped firing. Cylinder 6 fired continuously after about 5 seconds of non-fired cycling, and cylinder 1 fired continuously after about 20 seconds of runtime. Once the last cylinder fired continuously, the opacity decreased rapidly to zero.

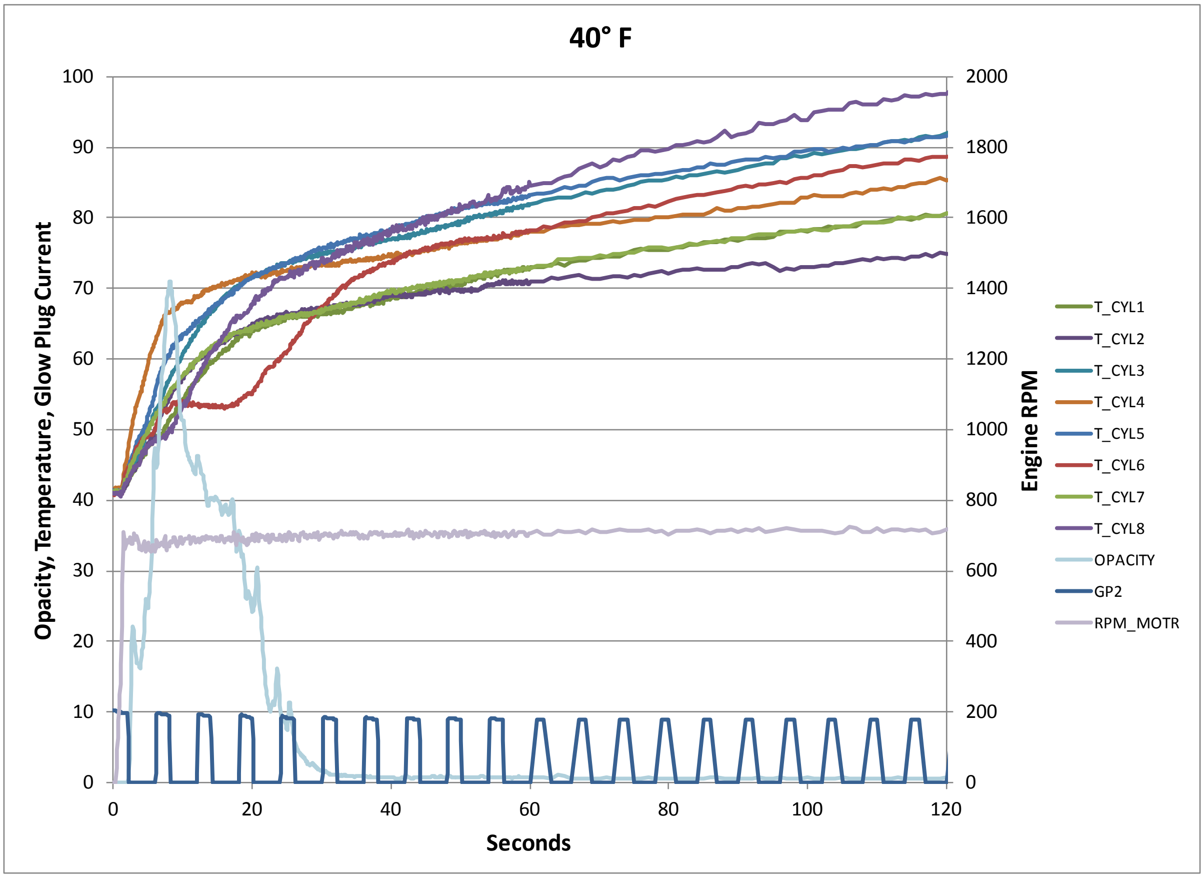

Figure 27. 39.5 Cetane Cold Start at 40 °F

At 20 °F, the engine was only able to start with the use of glow plugs. As seen in Figure 28, the engine started immediately with no hesitation, firing on all cylinders. Cylinder 1 started firing intermittently at about the 10 seconds mark, and was fully stable after 100 seconds of runtime. The data set continues in Figure 29 on the following page.

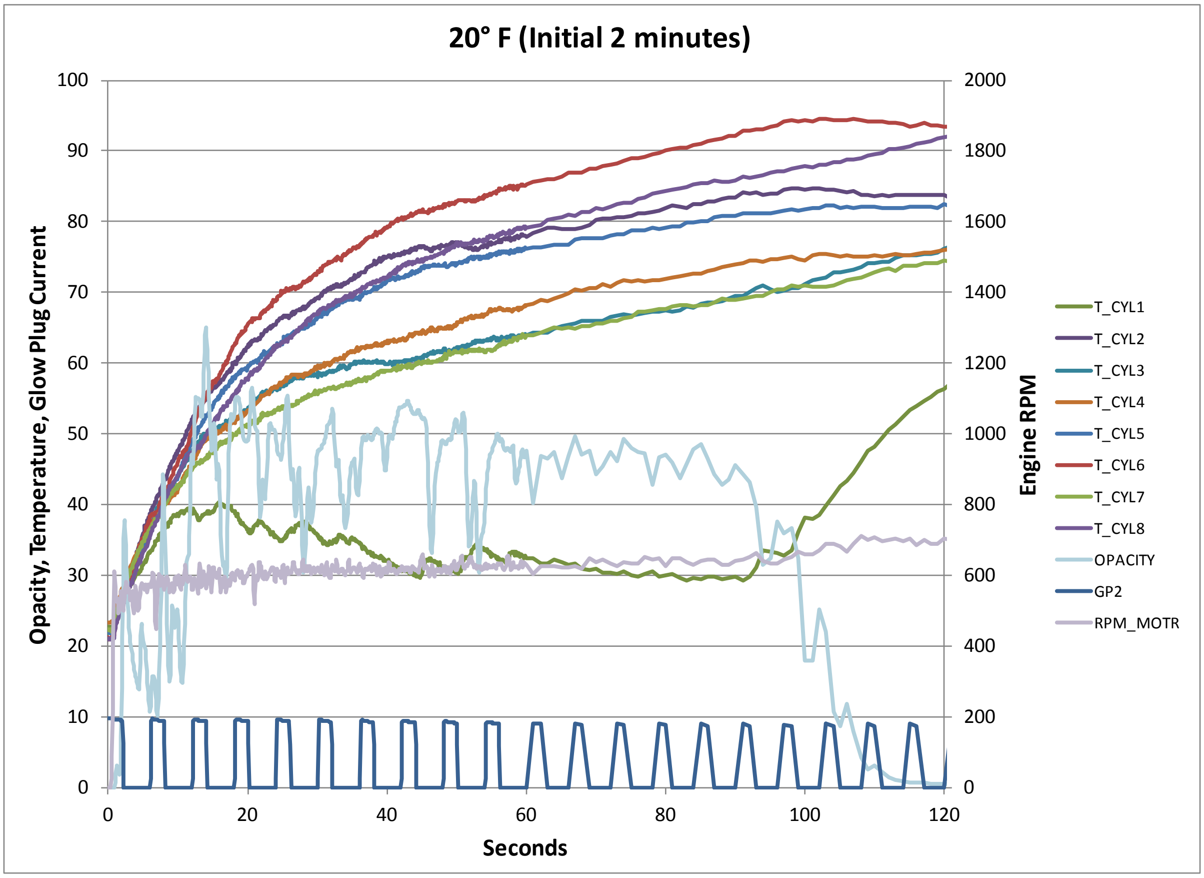

Figure 28. 39.5 Cetane Cold Start at 20 °F – Initial 2 minutes

Even though the engine was firing continuously after about 100 seconds, warm up continued until after the glow plugs ceased operation. From the changing exhaust temperatures, it appears that cylinder 6 was carrying the majority of the frictional load from cylinder 1 not firing. After engine stabilization, cylinder 2 diverged from the rest in terms of exhaust temperature. This may be a result of some slight performance difference due to the presence of the pressure transducer and injector lift sensor.

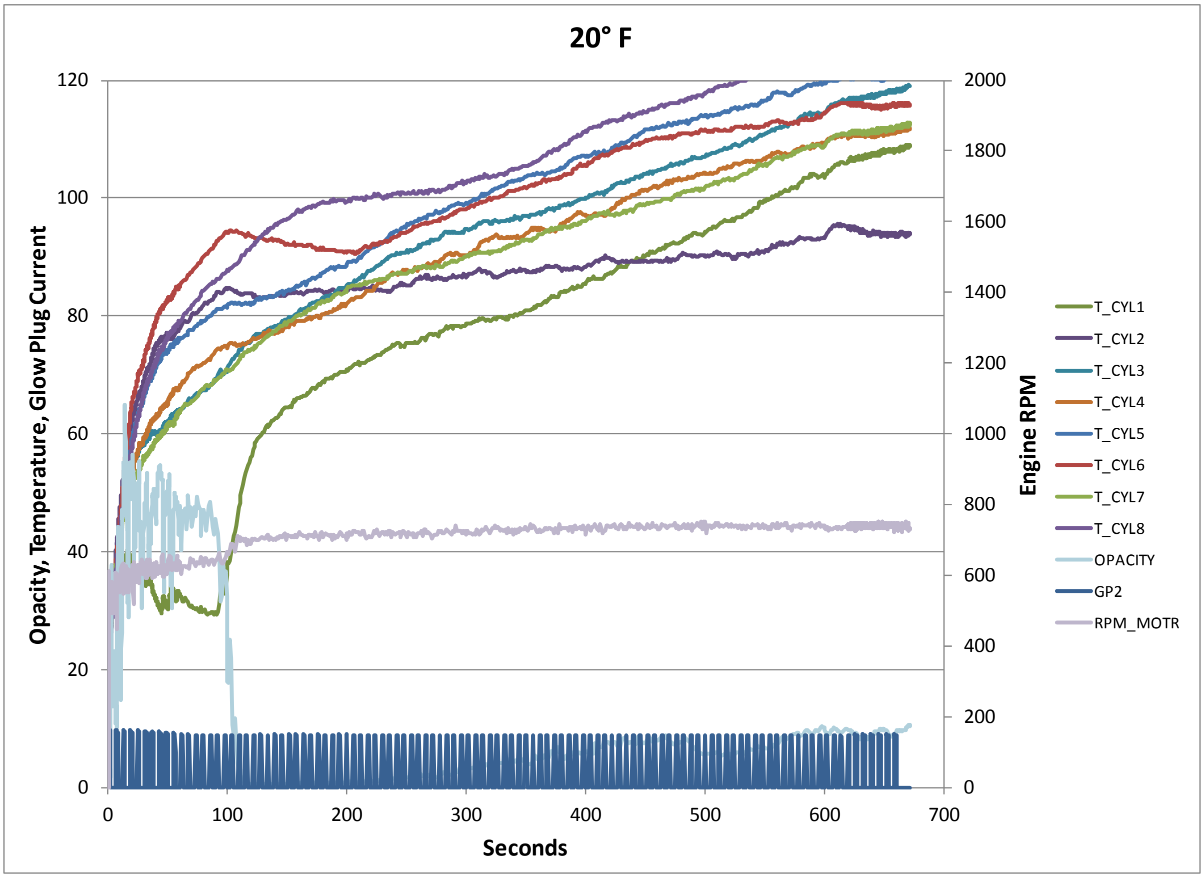

Figure 29. 39.5 Cetane Cold Start at 20 °F

At 0 °F, the engine was only able to start with the use of glow plugs. As seen in Figure 30, the engine continued to crank for about 20 seconds before the first firing event. Of all the cylinders, only 5 and 8 fired continuously. Cylinder 6 had a few seconds of non-firing just before 25 seconds and continued firing thereafter. Cylinders 2 and 4 were also fully firing by the 30 second mark after a few misfire events. Cylinders 1, 3 and 7 ceased firing entirely by the 60 second mark. The data set continues in Figure 31 on the following page.

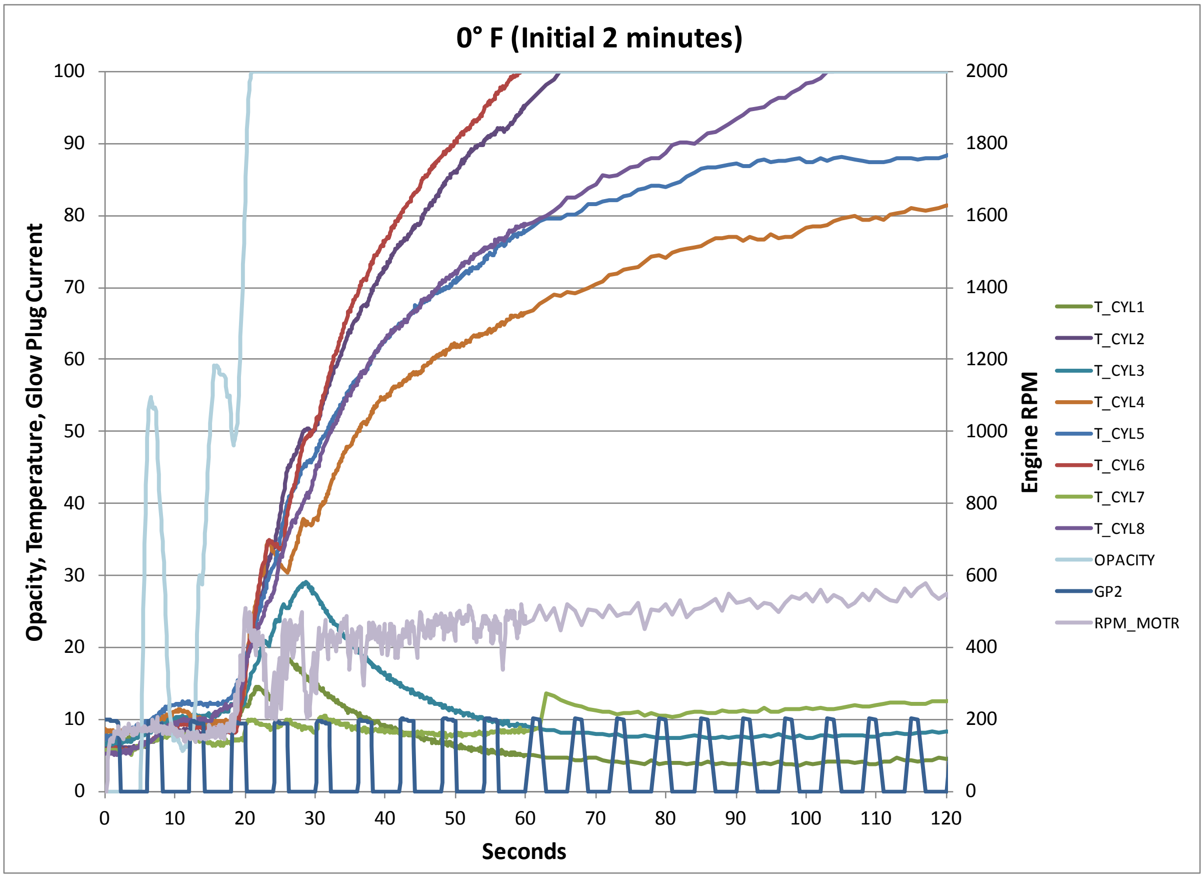

Figure 30. 39.5 Cetane Cold Start at 0 °F – Initial 2 minutes

Cylinder 7 started to re-light after the 120 second mark and was running continuously by 160 seconds. Cylinder 3 started to re-light after the 130 second mark and was running continuously by 270 seconds. Cylinder 1 started to re-light after the 380 second mark and was running continuously by 430 seconds.

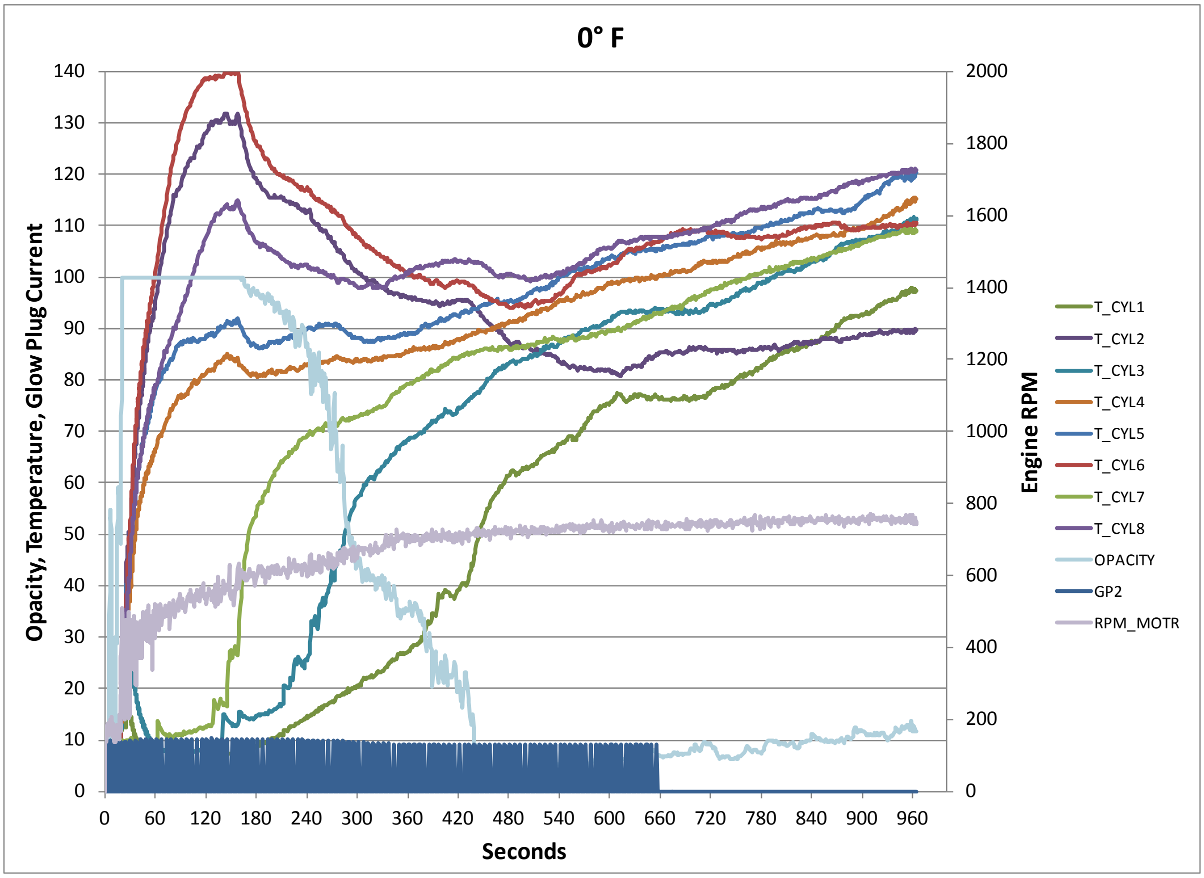

Figure 31. 39.5 Cetane Cold Start at 0 °F

The -20 °F data set for this fuel was not taken due to a failure of the starting motor. The 39.5 cetane fuel was the last one tested in this program, and the starter motor failure occurred approximately 6 weeks prior to the end of the contract. The motor repair took 4 weeks, but with only 2 weeks remaining in the contractual period, there was not enough time to re-install and complete testing.

7.6 GEP COLD START ON 36.4 CETANE FUEL

At 40 °F, and with the aid of the glow plugs, the engine fired immediately on all cylinders (Figure 32). However, a few seconds after starting, cylinder 6 stopped firing. Cylinder 6 fired continuously after about 25 seconds of runtime and the opacity decreased rapidly to zero.

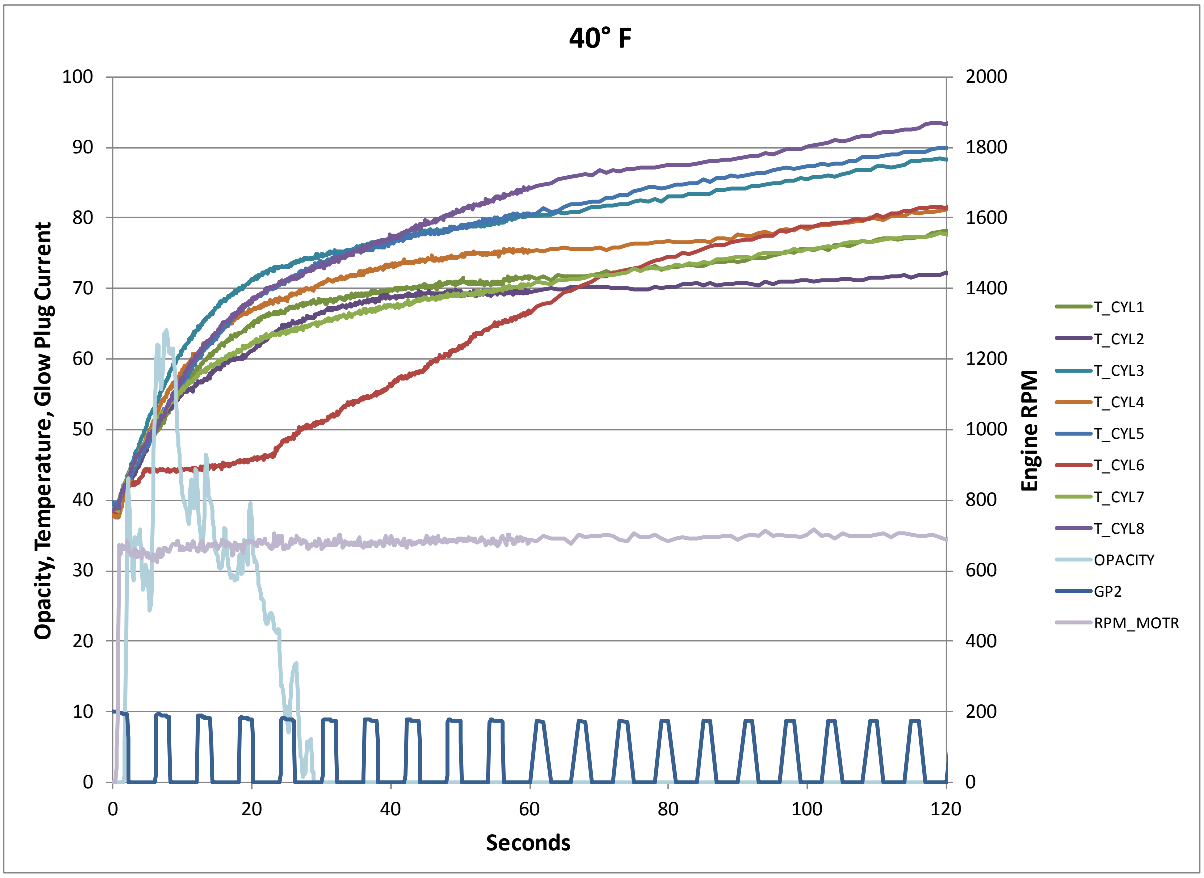

Figure 32. 36.4 Cetane Cold Start at 40 °F

At 20 °F, the engine was only able to start with the use of glow plugs. As seen in Figure 33, the engine started immediately with no hesitation, firing on all cylinders. Cylinders 1 and 8 both cut out at about the 10 seconds mark. Cylinder 8 then fired intermittently from about 10 to 120 seconds and fired continuously after. Cylinder 1 had about 4 firing events in that same time period. From 120 to about 220 seconds, cylinder 1 was firing intermittently with some small periods of continuous firing. After 220 seconds cylinder 1 was fully stable.

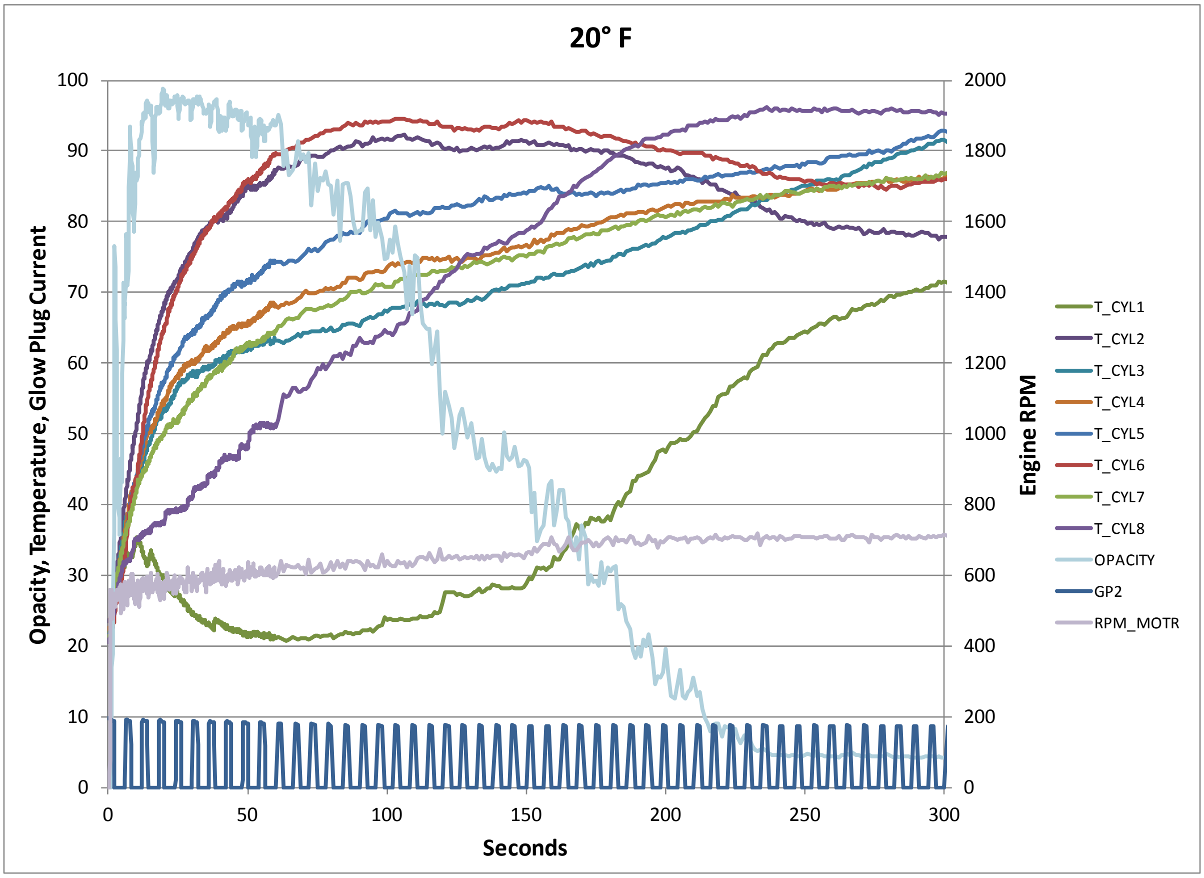

Figure 33. 36.4 Cetane Cold Start at 20 °F

At 0 °F, the engine was only able to start with the use of glow plugs. As seen in Figure 34, the engine started immediately with no hesitation, firing on all cylinders. But after the first 5 seconds of operation cylinders 1, 3 and 8 started to misfire. By the 15 second mark, all three were fully out. The exhaust temperature for cylinder 8 continued to rise due to the piping configuration; it was getting some heat from cylinders 2, 4, and 6 which were all firing. The data set continues in Figure 35 on the following page.

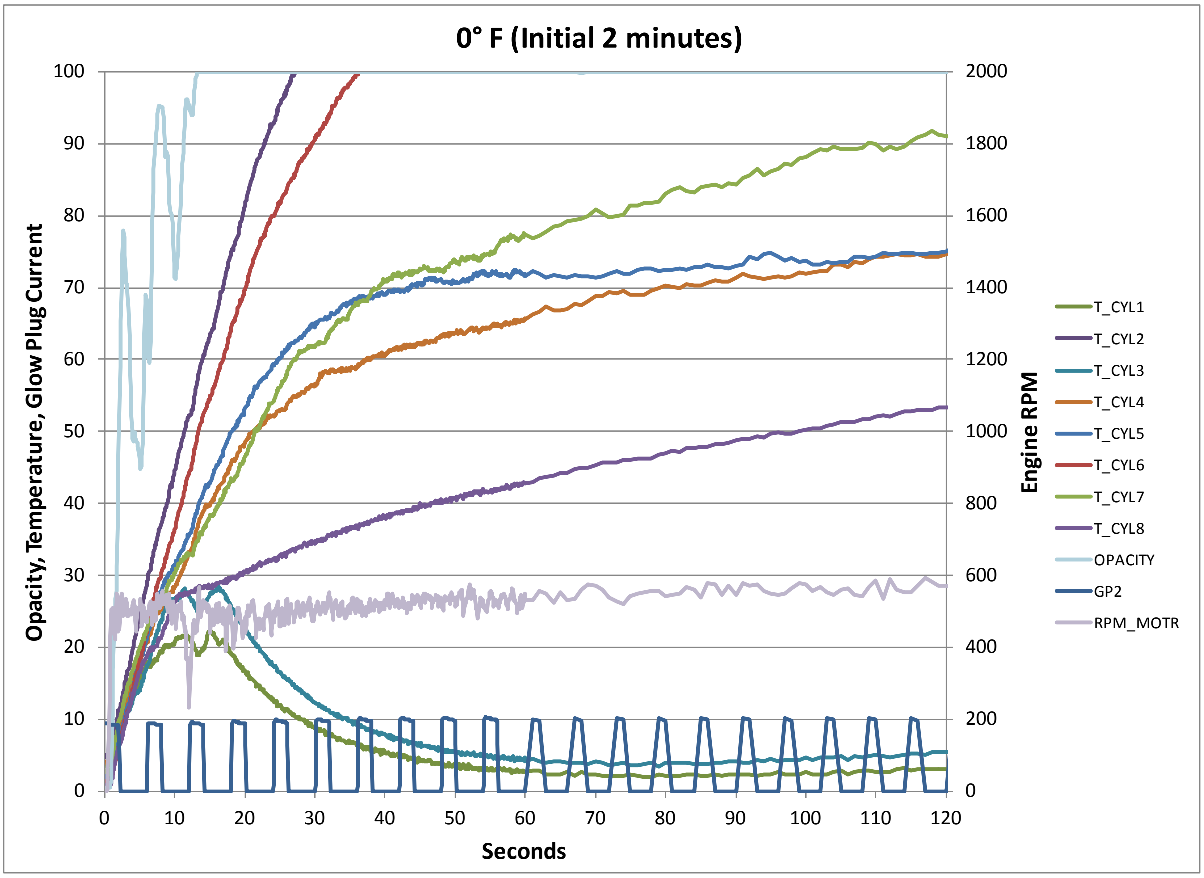

Figure 34. 36.4 Cetane Cold Start at 0 °F – Initial 2 minutes

Cylinder 8 started to re-light after the 125 second mark and was running continuously by 180 seconds. Cylinder 3 started to re-light after the 175 second mark and was running continuously by 310 seconds. Cylinder 1 started to re-light after the 380 second mark and was running continuously by 470 seconds.

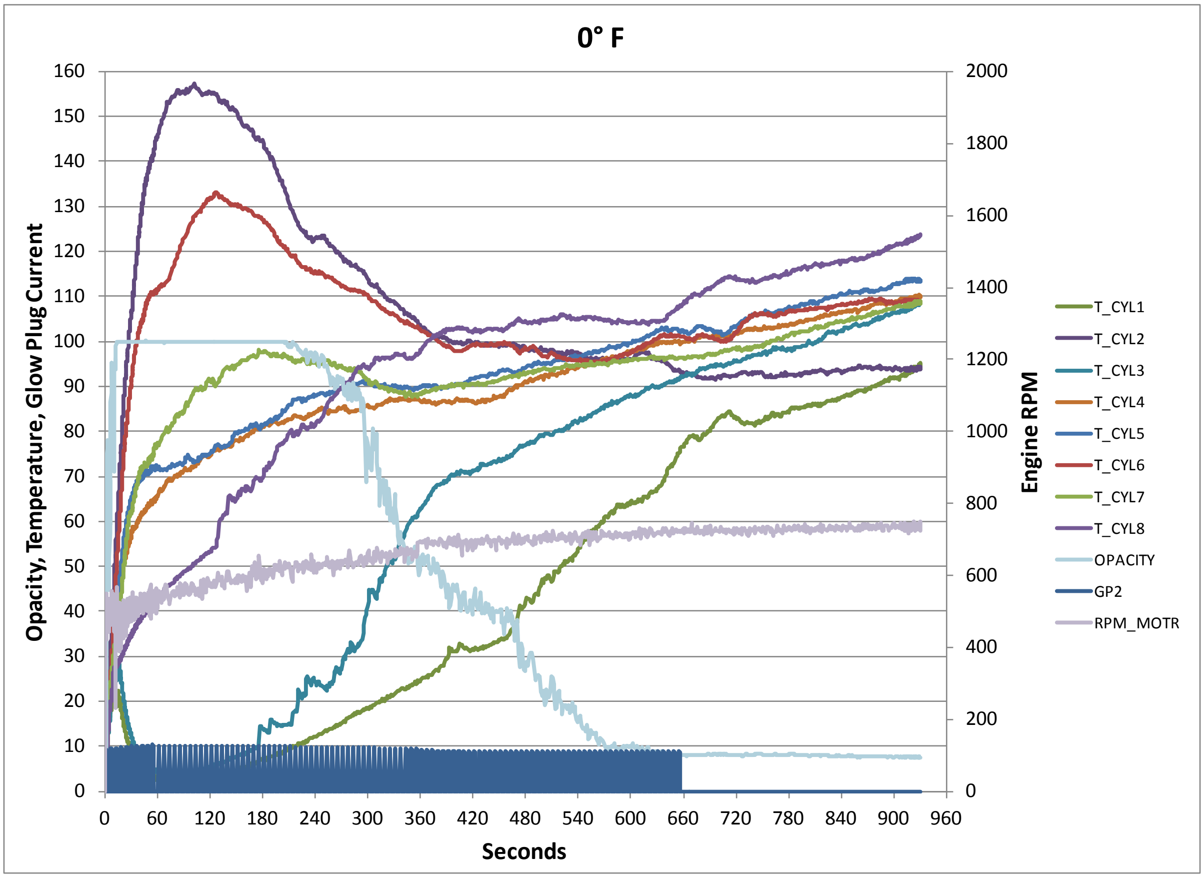

Figure 35. 36.4 Cetane Cold Start at 0 °F

At -20 °F, the engine was only able to start with the use of glow plugs. As seen in Figure 36, the engine started immediately with no hesitation, firing on all cylinders. But after the first 10 seconds of operation cylinders 1, 7 and 8 started to misfire. By the 30 second mark, all three were fully out. The exhaust temperature for cylinder 8 continued to rise due to the piping configuration; it was getting some heat from cylinders 2, 4, and 6 which were all firing. The data set continues in Figure 37 on the following page.

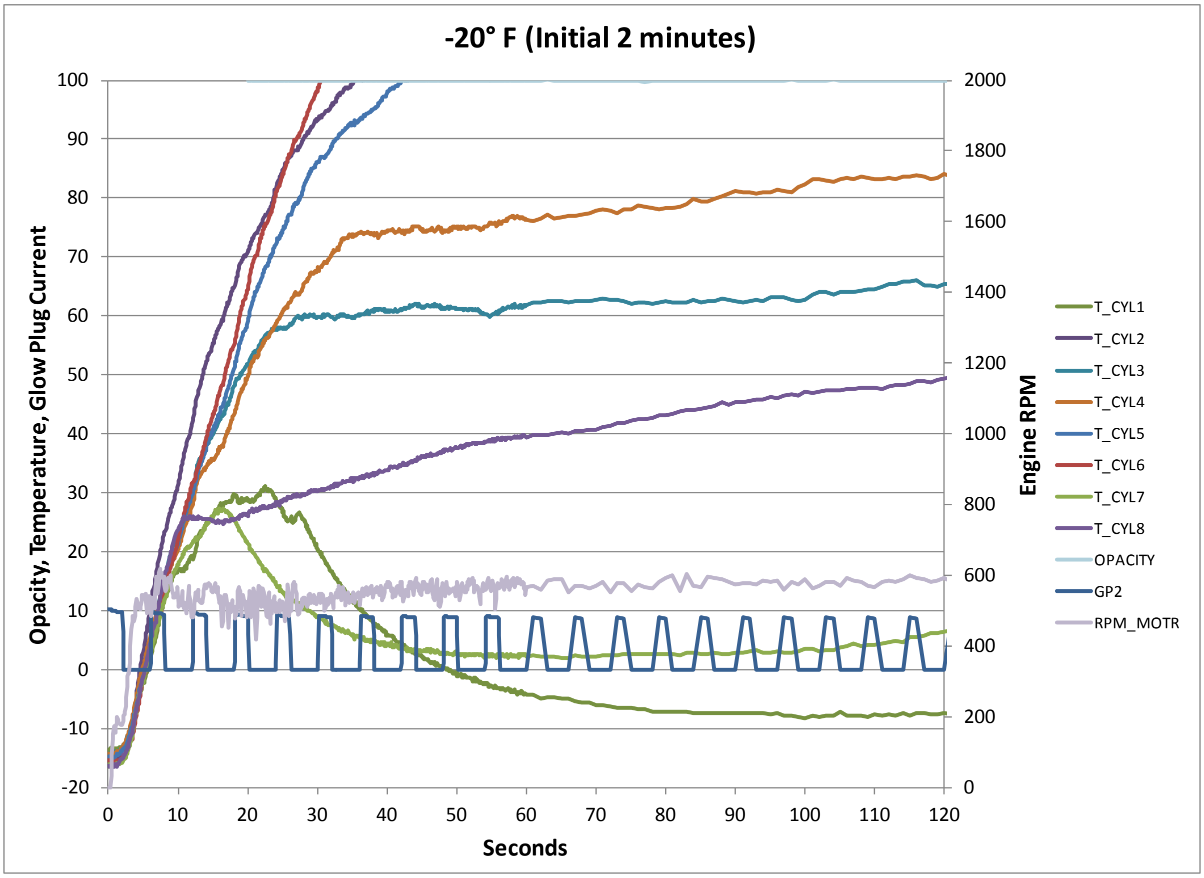

Figure 36. 36.4 Cetane Cold Start at -20 °F – Initial 2 minutes

With an increase of the left y-axis scaling, cylinder 5 also had some intermittent firing from about 50 to 150 seconds. Cylinder 7 started to re-light after the 270 second mark and was running continuously by 330 seconds. Cylinder 8 started to re-light after the 290 second mark and was running continuously by 440 seconds. Cylinder 1 started to re-light after the 570 second mark, but continued without success until it was running continuously after 900 seconds of runtime. The opacity data in this figure was limited due to a loose connecting wire. The problem was corrected prior to the next run.

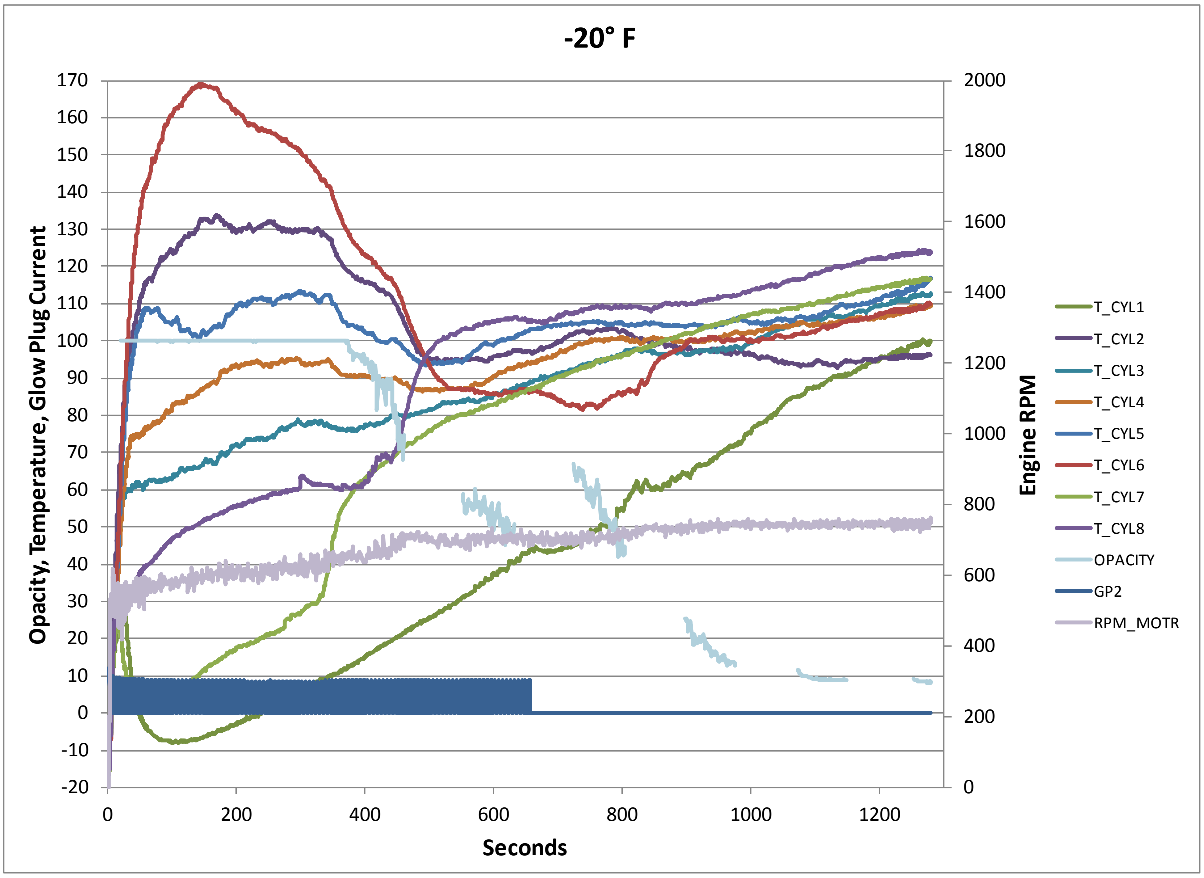

Figure 37. 36.4 Cetane Cold Start at -20 °F

7.7 GEP Cold Start on 33 Cetane Fuel

At 40 °F, the glow plugs were only enabled for 10 seconds prior to ignition, and disabled thereafter. The engine was able to start, but 3 of the cylinders immediately quit firing. As seen in Figure 38 , cylinder 2 was the first to relight, followed 30 seconds later by cylinder 7, and after another 30 seconds cylinder 8 reignited. Although the temperature of cylinder 2 does not increase with time as the other cylinders, combustion was occurring as indicated by the low opacity values.

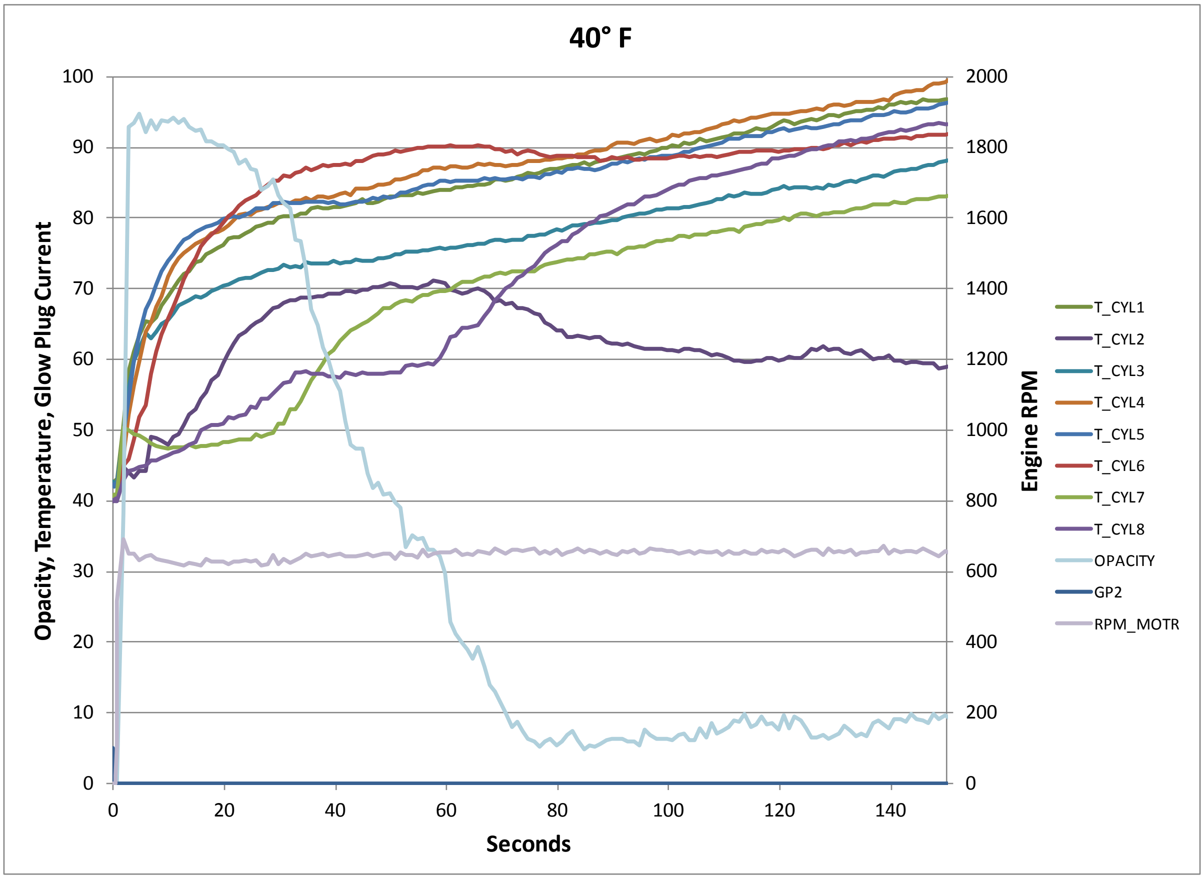

Figure 38. 33 Cetane Cold Start at 40 °F

At 20 °F, the engine was only able to start with the use of glow plugs. As seen in Figure 39, the engine started immediately with no hesitation, firing on all cylinders. However, cylinder 4 stopped firing a few seconds after ignition, then resumed about the time cylinder 6 stopped firing. Cylinder 6 fired intermittently until full relight around 300 seconds.

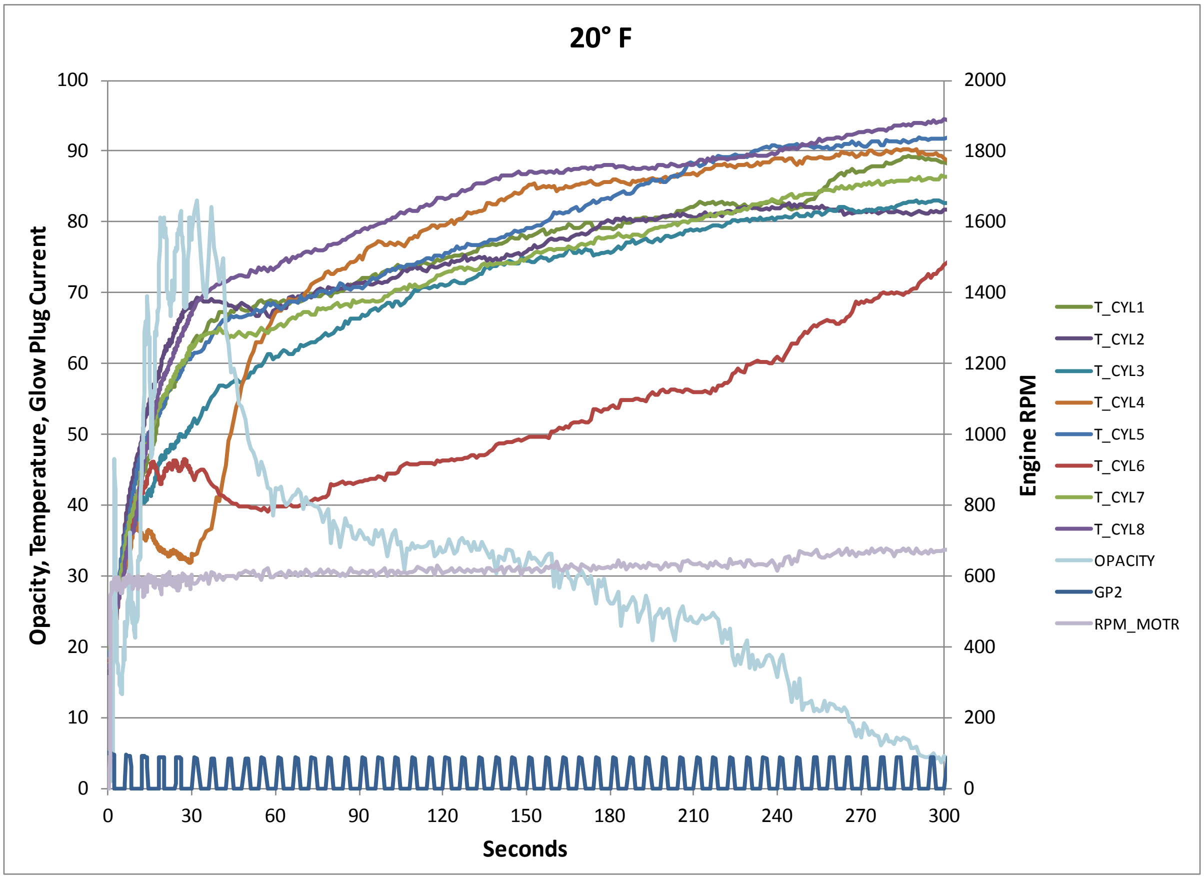

Figure 39. 33 Cetane Cold Start at 20 °F

At 0 °F, the engine was again only able to start with the use of glow plugs. As seen in Figure 40, the engine started immediately with no hesitation, firing on all cylinders. After 20 seconds, cylinder 6 stopped firing followed by cylinder 1 at about 60 seconds. The data set is continued in Figure 41 on the following page.

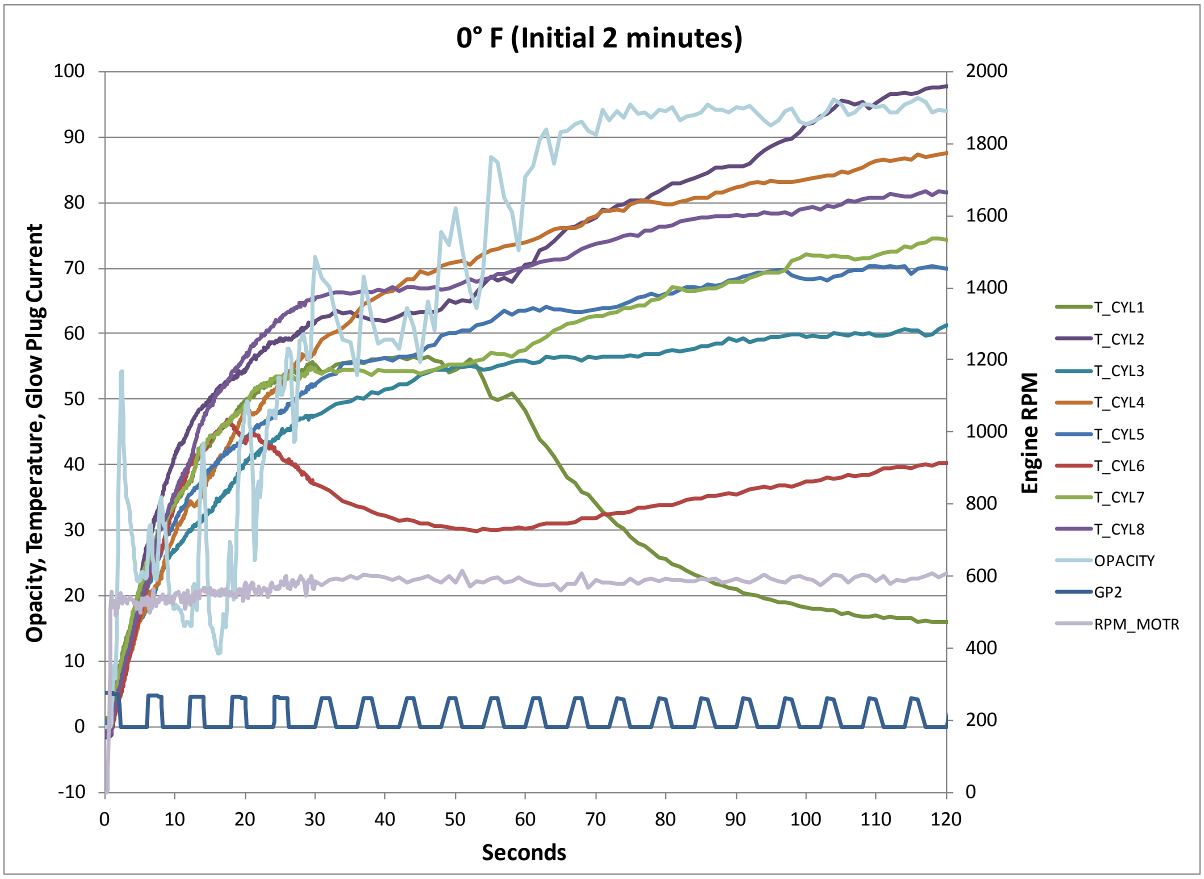

Figure 40. 33 Cetane Cold Start at 0 °F – Initial 2 minutes

Cylinder 6 continued to gain heat from the surrounding cylinders and started firing intermittently at about 120 seconds. Around 300 seconds consistent combustion was achieved on cylinder 6. Cylinder 1 did not fully relight until 480 seconds after ignition began.

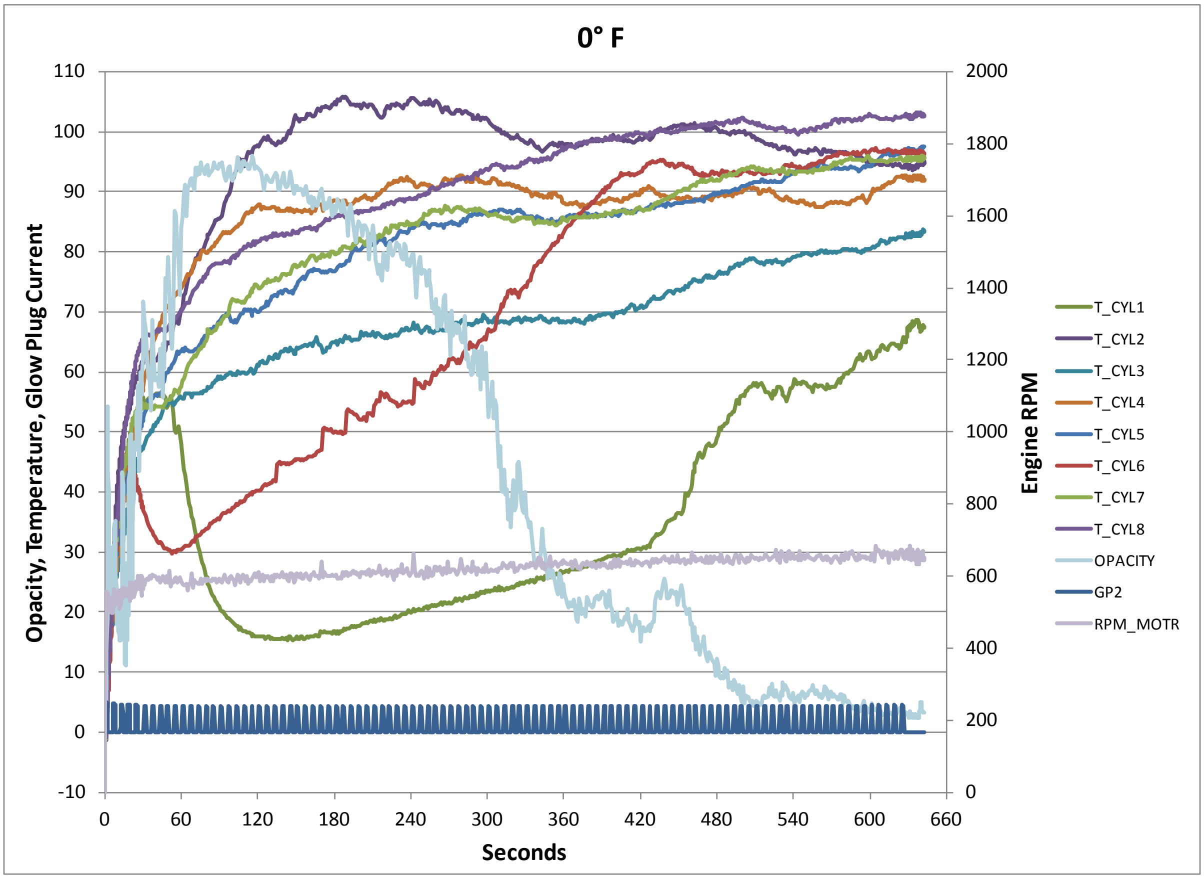

Figure 41. 33 Cetane Cold Start at 0 °F

At -20 °F, the engine was only able to start with the use of glow plugs. As seen in Figure 42, the engine started immediately with no hesitation, firing on all cylinders. The opacity decreased for the first 30 seconds until cylinders 4 and 6 stopped firing. The data is continued in Figure 43 on the following page.

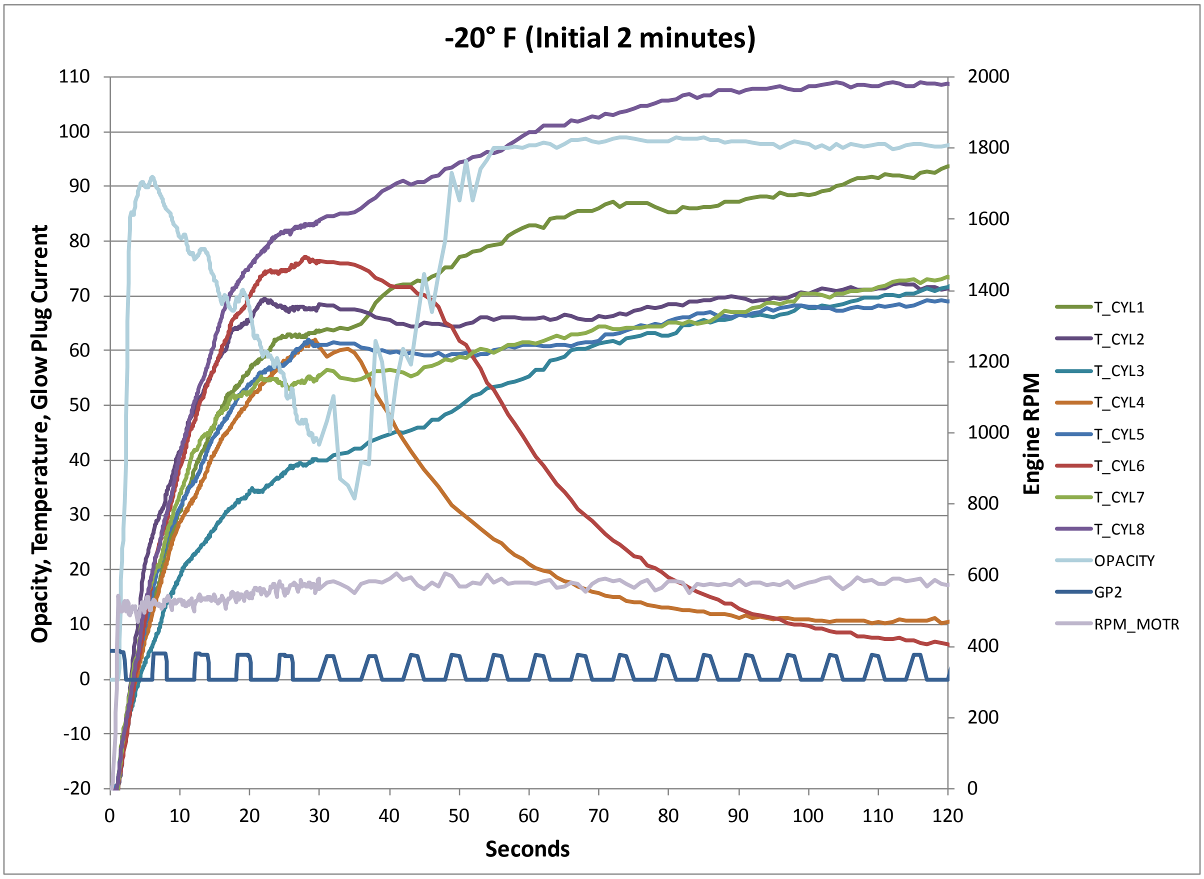

Figure 42. 33 Cetane Cold Start at -20 °F – Initial 2 minutes

For almost a full 9 minutes the engine slowly warmed up on 6 of the 8 cylinders. Between 500 and 600 seconds, cylinders 4 and 6 attempted to relight, and fired occasionally for another 500 seconds. After 630 seconds of operation, the glow plugs were automatically disabled according to the test programming. Cylinder 4 fully relit after almost 17 minutes, and cylinder 6 relit successfully a full 20 minutes after ignition.

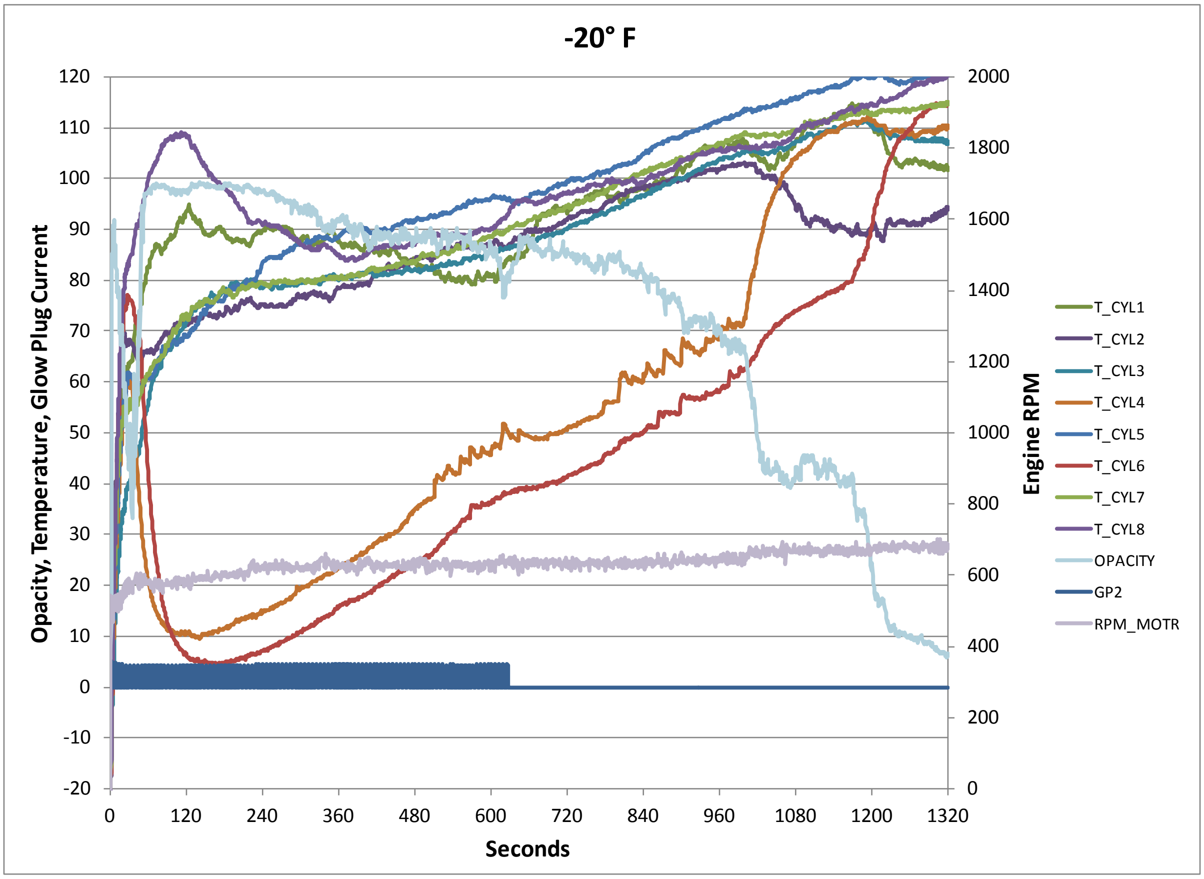

Figure 43. 33 Cetane Cold Start at -20 °F

7.8 GEP Cold Start on 31.3 Cetane Fuel

At 40 °F, and with the aid of the glow plugs, the engine fired immediately on all cylinders (Figure 42). However, a few seconds after starting, cylinders 6 and 8 stopped firing. Cylinder 8 fired continuously after about 15 seconds of non-fired cycling, and cylinder 6 fired intermittently after about 30 seconds of runtime. Once cylinder 6 fired continuously at about 180 seconds of runtime, the opacity stabilized near zero.

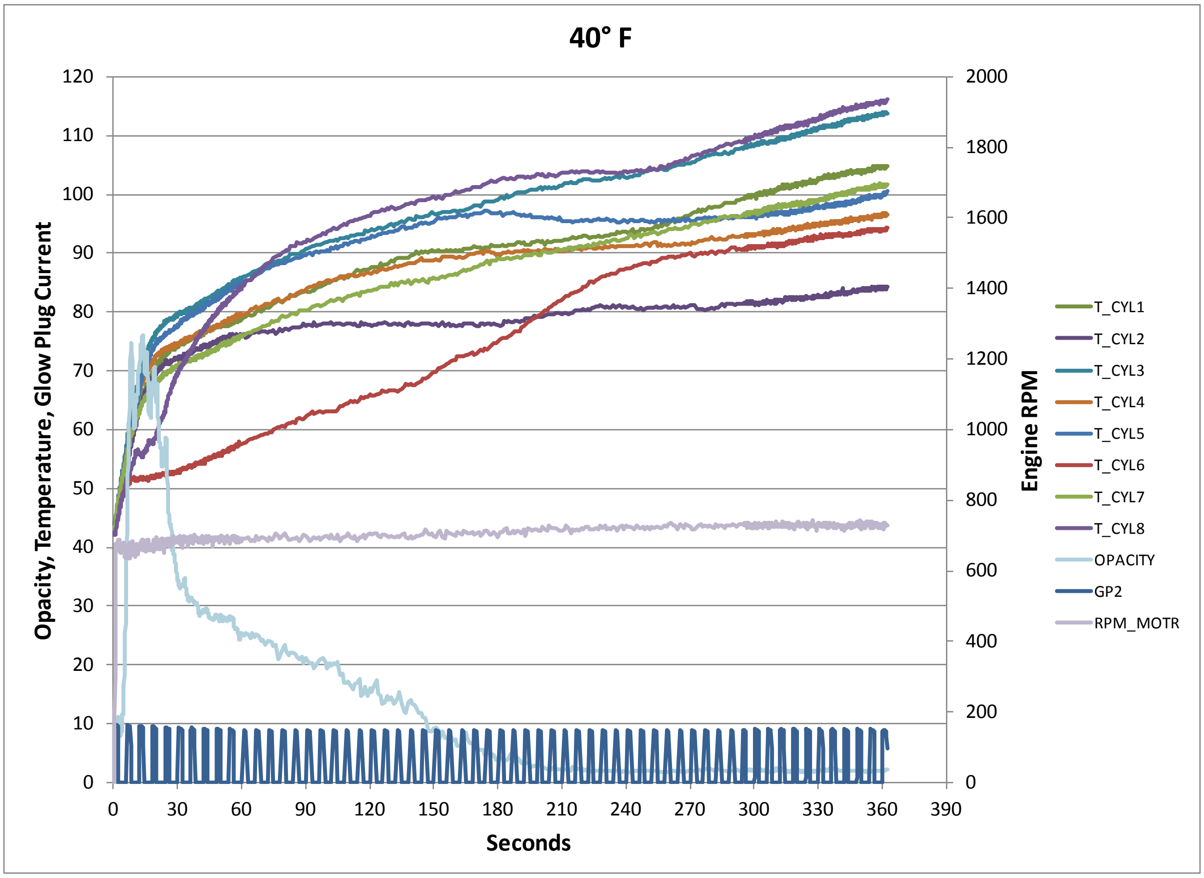

Figure 44. 31.3 Cetane Cold Start at 40 °F

At 20 °F, the engine was only able to start with the use of glow plugs. As seen in Figure 45, the engine started immediately with no hesitation, firing on all cylinders. Cylinders 1, 3, and 8 cut out at about the 5 seconds mark. Cylinder 8 then fired intermittently from 45 to 150 seconds and fired continuously after. The data set continues in Figure 46 on the following page.

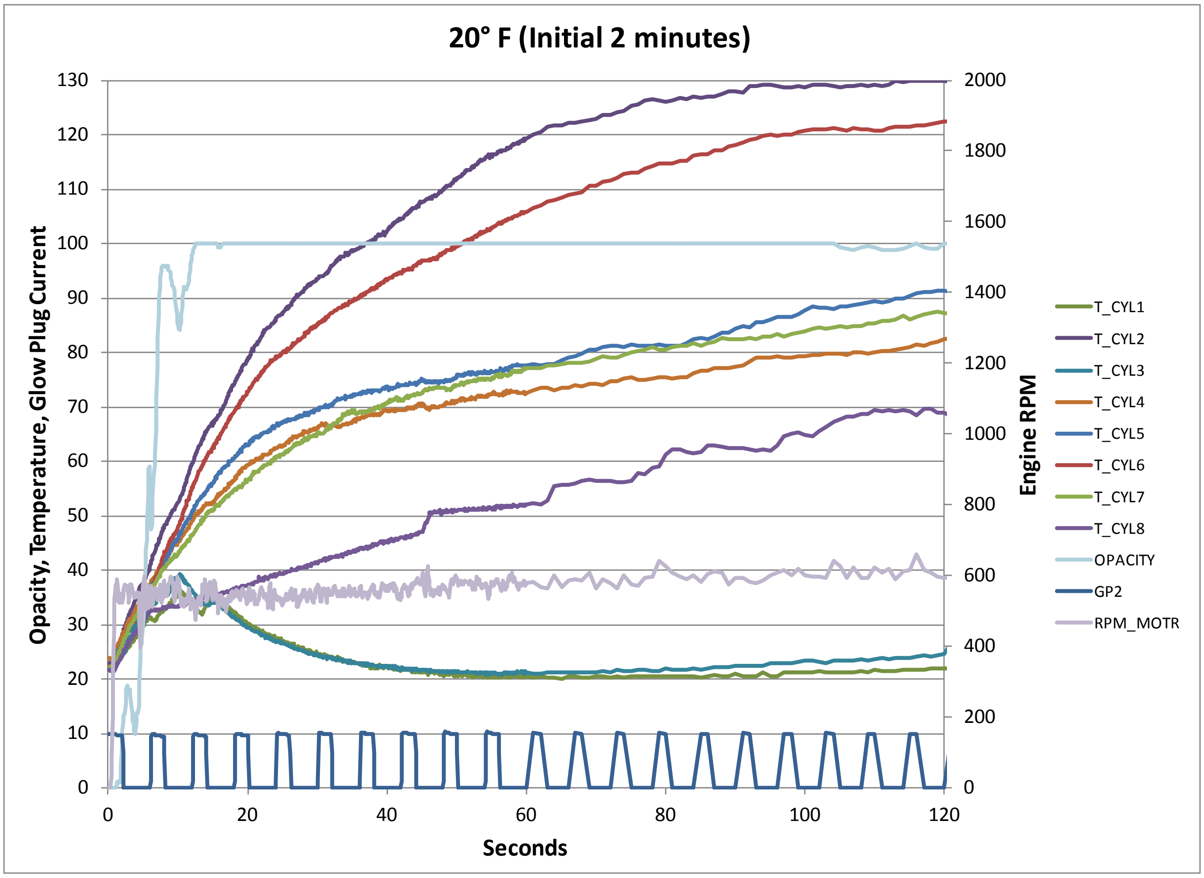

Figure 45. 31.3 Cetane Cold Start at 20 °F – Initial 2 minutes

Cylinder 3 attempted re-light from 110 to 200 seconds, and fired continuously thereafter. Cylinder 1 also attempted re-light from 170 to 230 seconds and then stopped again. Firing very infrequently until about 400 seconds, cylinder 1 finally achieved re-light and stability after 440 seconds.

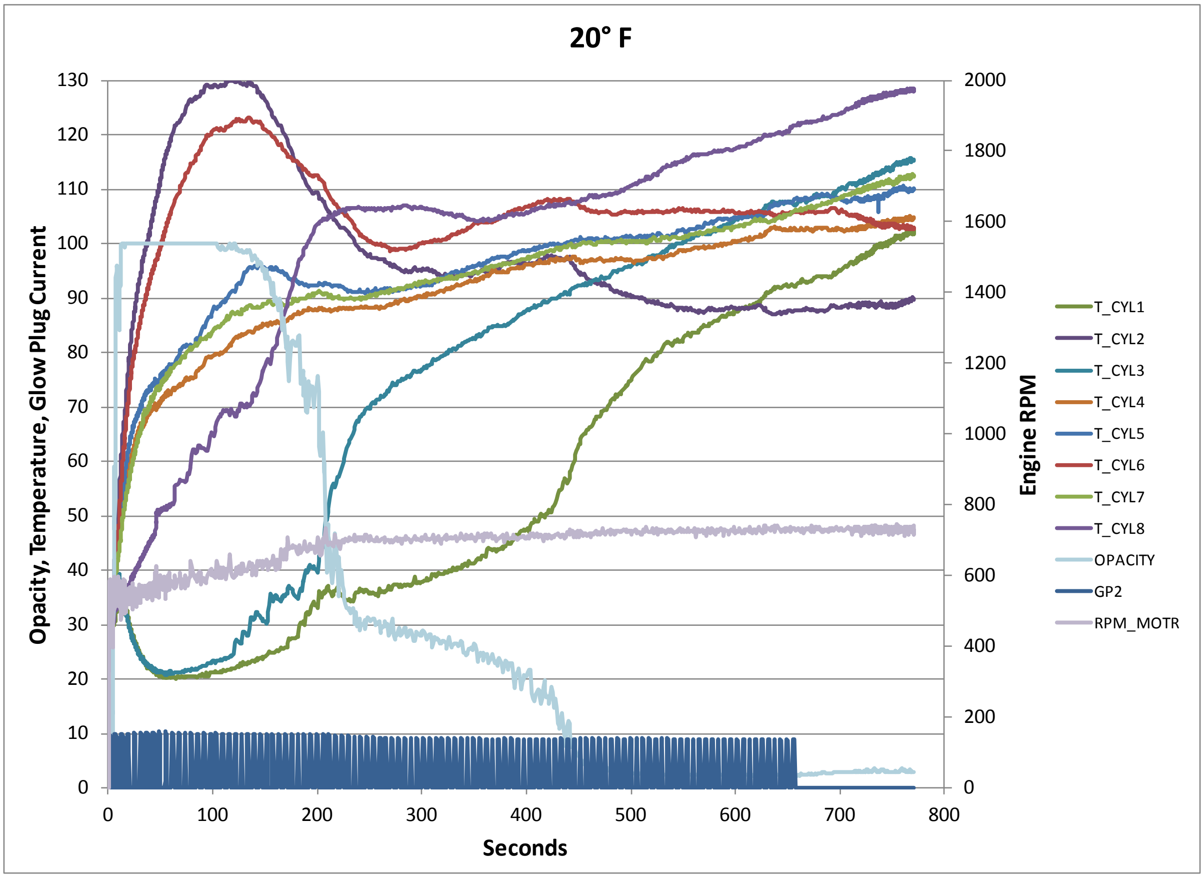

Figure 46. 31.3 Cetane Cold Start at 20 °F

At 0 °F, the engine was only able to start with the use of glow plugs. As seen in Figure 47, the engine started immediately with no hesitation, firing on all cylinders. But after the first 5 seconds of operation cylinders 1, 3 and 8 started to misfire. By the 20 second mark, all three were fully out. The exhaust temperature for cylinder 8 continued to rise due to the piping configuration; it was getting some heat from cylinders 2, 4, and 6 which were all firing. The data set continues in Figure 48 on the following page.

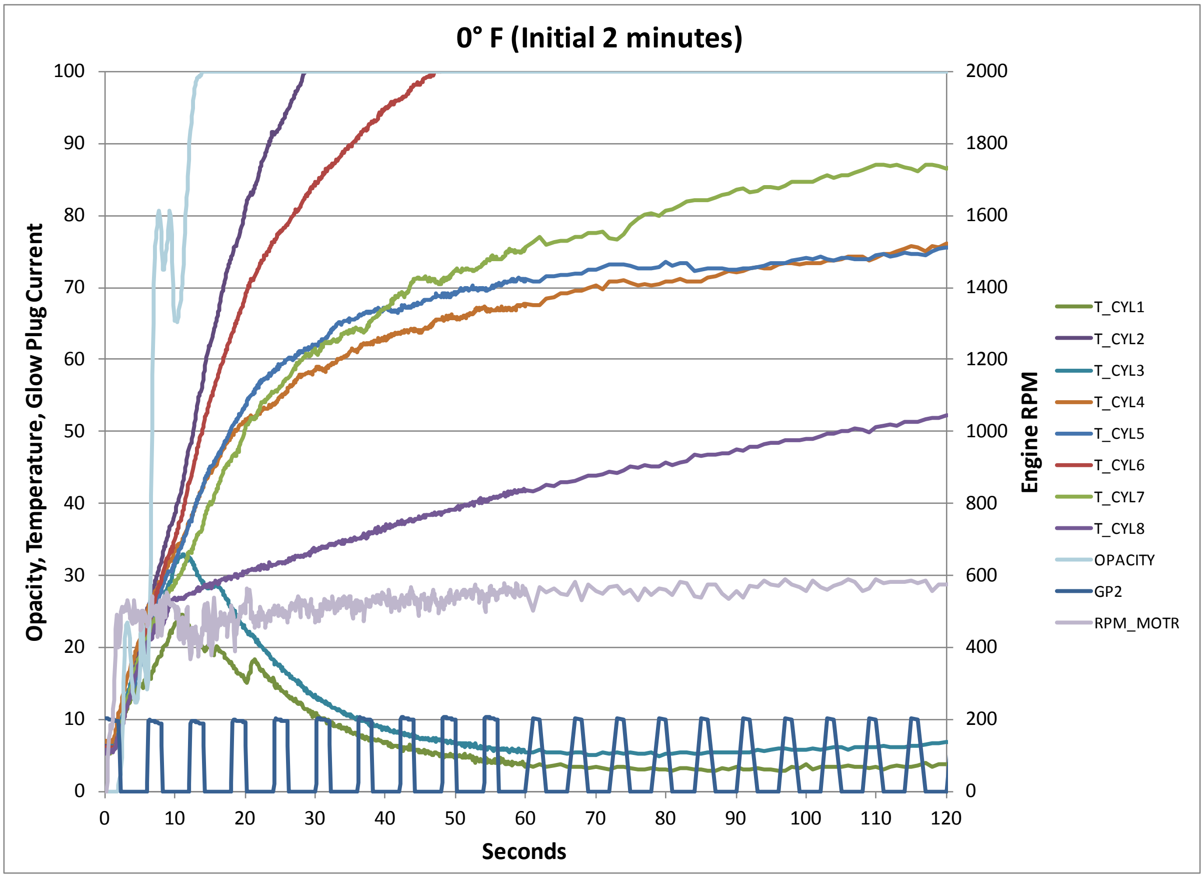

Figure 47. 31.3 Cetane Cold Start at 0 °F – Initial 2 minutes

Cylinder 8 started to re-light after the 210 second mark and was running continuously by 320 seconds. Cylinder 3 started to re-light after the 390 second mark and was running continuously by 440 seconds. Cylinder 1 started to re-light after the 610 second mark, but went out again 70 seconds later. Cylinder 1 started to re-light again after the 780 second mark and was running continuously by 850 seconds.

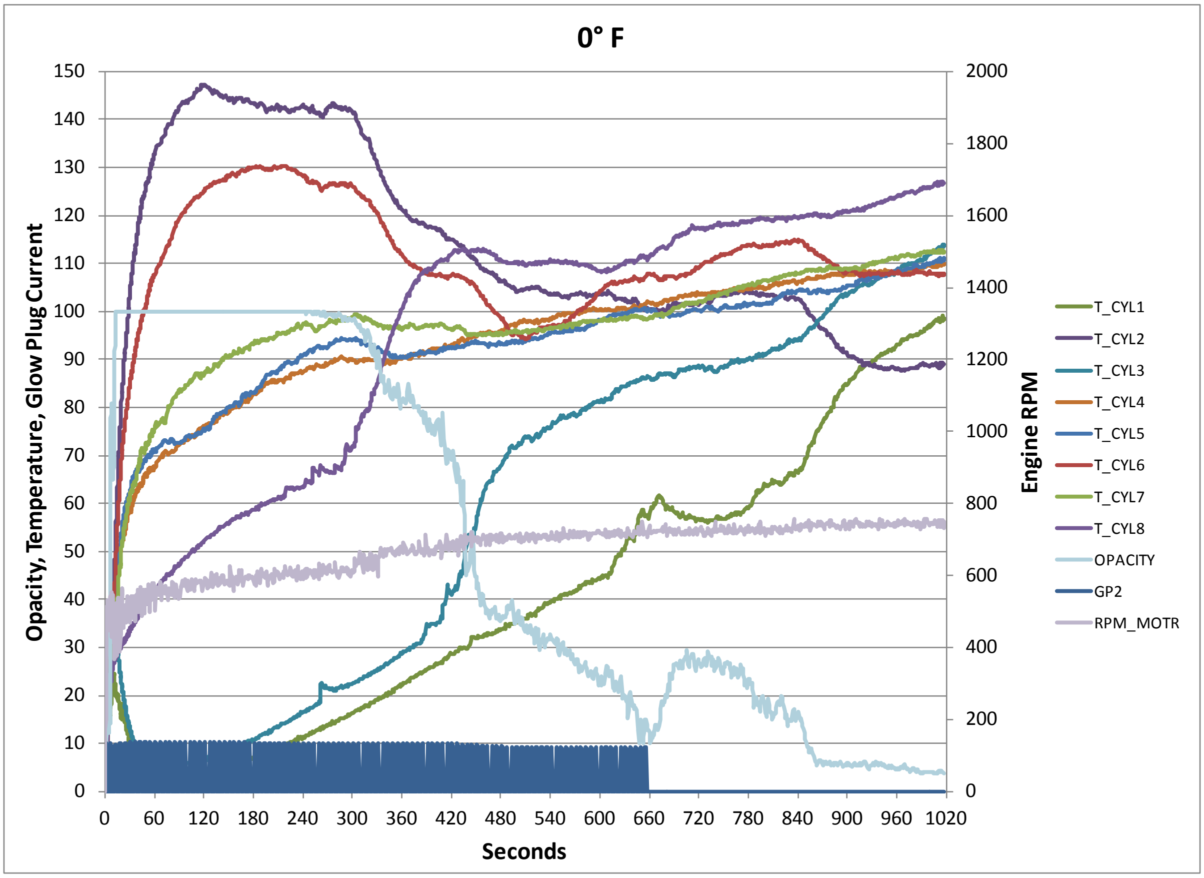

Figure 48. 31.3 Cetane Cold Start at 0 °F

At -20 °F, the engine was only able to start with the use of glow plugs. As seen in Figure 49, the engine started after about 6 seconds of cranking, firing on all cylinders. But after the first 4 seconds of operation cylinders half of the cylinders (1, 3, 7, and 8) started to misfire. By the 33 second mark, all four were fully out. The exhaust temperature for cylinder 8 continued to rise due to the piping configuration; it was getting some heat from cylinders 2, 4, and 6 which were all firing. The data set continues in Figure 50 on the following page.

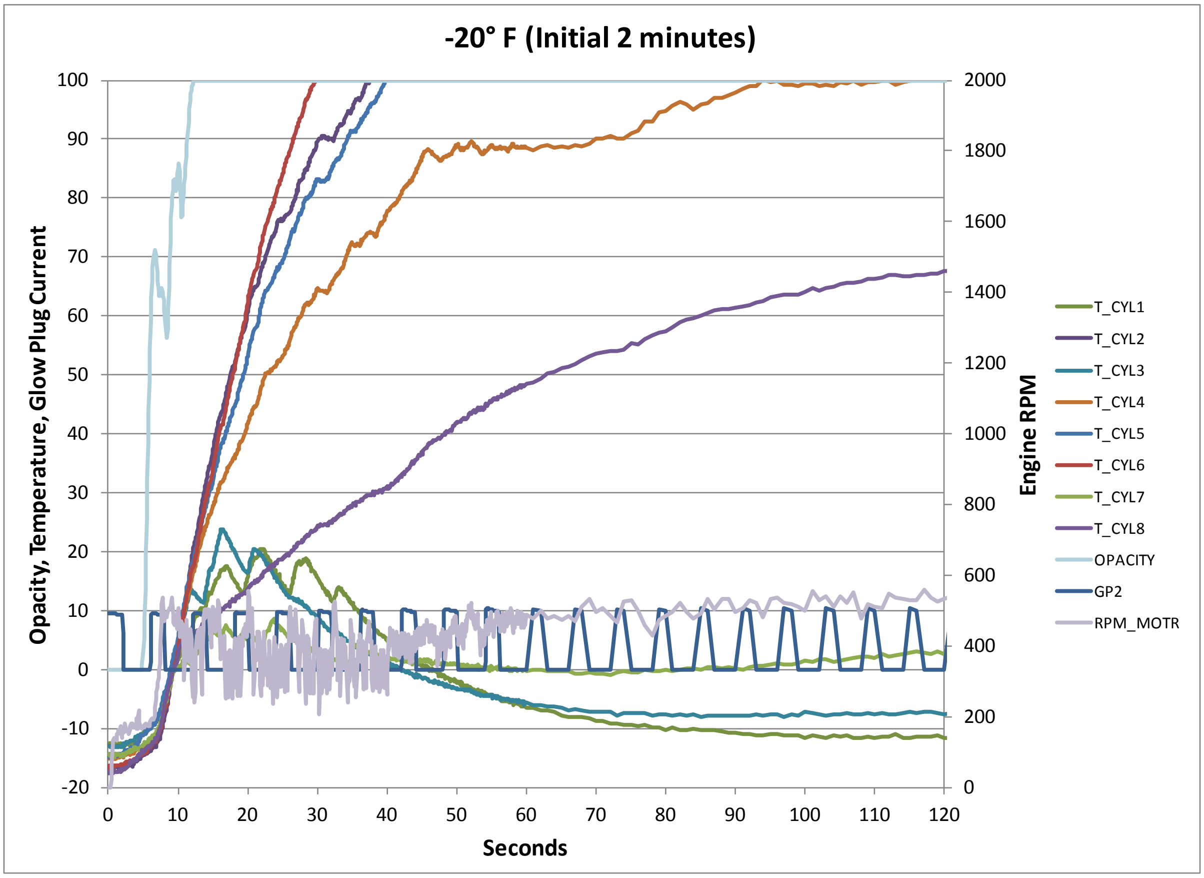

Figure 49. 31.3 Cetane Cold Start at -20 °F – Initial 2 minutes

With an increase of the left y-axis scaling, cylinders 4 and 5 also had some intermittent firing from about 50 to 70 seconds. During this 20 second window, the engine was being driven almost entirely by cylinders 2 and 6.

Cylinder 7 started to re-light first after the 360 second mark and was running continuously by 400 seconds. Cylinder 8 started to re-light after the 400 second mark and was running continuously by 550 seconds. Cylinder 3 had a few firing events, but did not start to re-light in earnest until 830 seconds of runtime had elapsed. After 910 seconds, cylinder 3 was firing continuously. Cylinder 1 started to re-light after about the 920 second mark, and was running continuously after 1100 seconds of runtime.

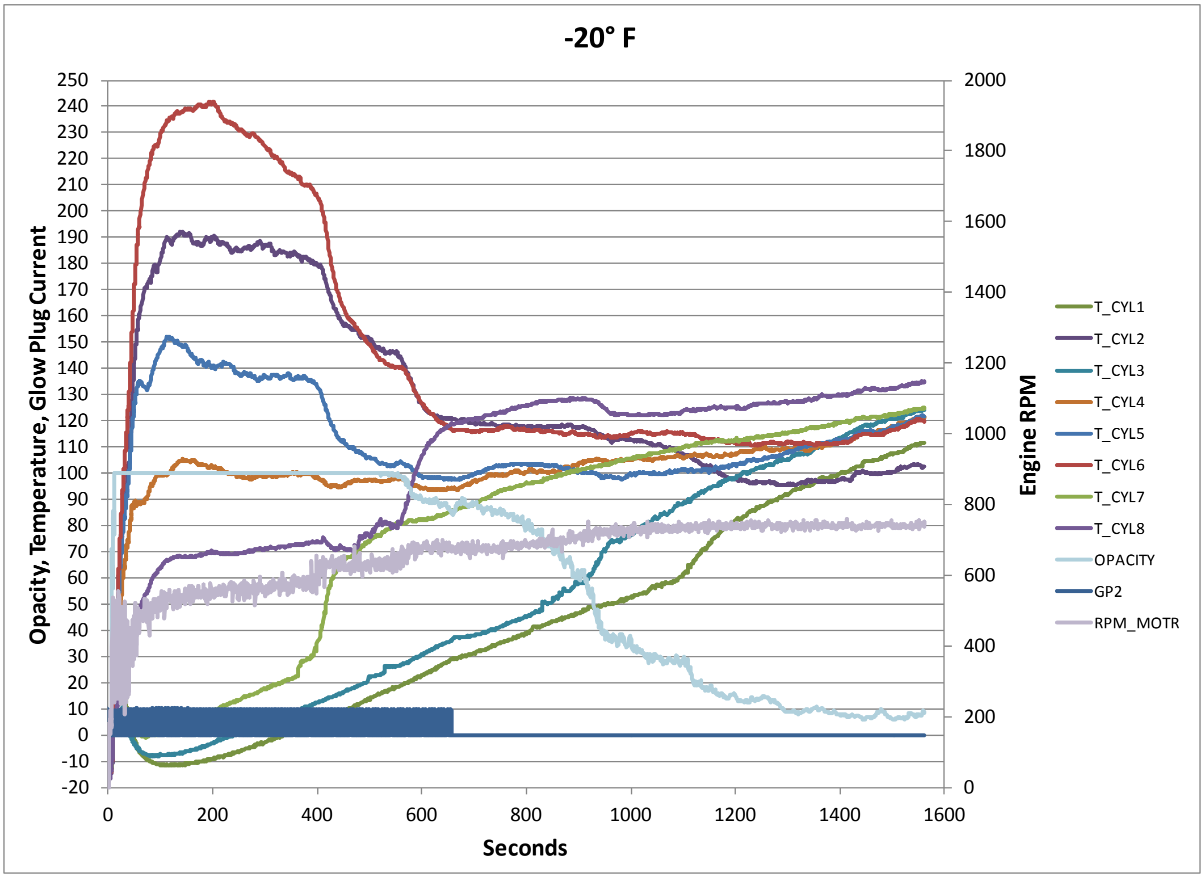

Figure 50. 31.3 Cetane Cold Start at -20 °F

8.0 SUMMARY

The GEP 6.5L engine operating in the cold box was able to distinguish large differences in the fuel. Even at a relatively warm 40 °F, all fuels below 44 cetane were unable to start in the engine without the aid of glow plugs. While the highest cetane fuel did not experience any cylinders ceasing combustion after ignition until the temperature dropped to -20 °F, almost all other fuel/temperature test points experienced cylinder deactivation to some degree. In the worst case (lowest cetane, lowest temperature) there was about a 20 second window shortly after ignition, where only 2 cylinders were firing continuously.

Some clear trends are visible in this work. Namely that cetane remains a good indicator of overall cold start performance. Linear correlations were observed that related exhaust opacity, or unburned hydrocarbons, with engine stability and the number of cylinders firing. As the temperatures and cetane values decreased, the time it took for engine stability to occur increased.

For this GEP 6.5L engine, if starting aids such as glow plugs are inoperable, it is unlikely that fuels below 40 cetane will allow the engine to start when the ambient temperatures are at or below 40 °F. If starting aids such as glow plugs are fully functional, the engine will be difficult to start with fuels below 35 cetane and at temperatures at or below 40 °F.

There was one additional trend that showed up in the data, but was unexplored due to constraints of the SOW. As temperatures and cetane number decreased, the maximum exhaust gas temperature increased. This increase was most noticeable at the point when some cylinders were not firing. Prior to the start of this program, all fuel injection components were certified in their operation. The injection pump has a maximum spread value (line to line) for injected mass at rated RPM, but it is unknown how this translates at cranking speeds and very low temperatures. The fuel viscosity likely plays a role in this phenomenon, as the lower temperatures would decrease the pump internal leakage rates, and consequently increase delivered mass to a given injector. The low temperature performance properties of the injection system may be of interest for future testing.